Implementation Plan for Flexible Automation in U.S. Shipyards

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FOREWARD

This implementation Plan for Flexible Automation in U.S. Shipyards, commissioned by panel SP-10 of the Stip Production Committee, surveys current design and building practice in the shipbuilding industry and recommends a systematic approach to productivity improvement through flexible automation.

Flexible automation in this context is not limited either to robots or fabrication issues. It covers any technique that can deal with a class of similar jobs. It can be applied to associated automation opportunities in design, production planning, outfit planning, measuring, data analysis, process improvement, and other crucial areas that support fabrication, account for a large part of construction cost, and can benefit from automation. New construction, overhaul, repair, and ship modernization can all benefit.

To prepare the ground for automation, it is essential to gain increased understanding of planning and fabrication processes, and to rationalize design, fabrication, and outfitting. The best roadmap for accomplishing this lies in zone design/construction and the concept of the interim product. Following this roadmap will encourage the necessary coupling between customer, designer, planner, and fabricator.

An essential feature of enhanced productivity, and a requirement for automation, is rationalization of designs and processes. Even if there is little or no actual automation, this rationalization itself will save money and time, direct and indirect labor, initial work time and rework time.

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I. EXECUTIVE SUMMARY

A. Motivation

The purpose of this study is to formulate a strategy for implementation of flexible automation in U.S. shipyards. The authors are familiar with flexible automation, having advanced its art and applied it to many industrial products. Their experience in research, development and applications has led to a systematic approach to applying automation in manufacturing, and this approach has been followed during this study.

The essence of the approach is expressed in the following precepts.

- Automation is a "system problem" that requires attention to all phases of manufacturing--purchasing, design, information and material handling, fabrication and assembly processes, measurements, and data concerning costs, times and quality measures.
- The cost of making something and the potential for automating are influenced by its design, and design in turn is influenced by rules and specifications, state of knowledge about design principles, design aids like CZD, and the habits of designers. Rationalizing designs and processes will save money even if no automation technology is applied.
- The right way to decide what technology to apply to an automation candidate is to study that candidate until its technical and economic requirements are known, then create performance specifications for that technology, and buy, build, or develop it.
- In keeping with the above precepts, a summary precept is that identifying automation candidates, identifying design improvements, increasing knowledge about processes, and educating personnel must all be pursued in order to improve productivity.

B. Approach

The strategy for conducting the study was based on these precepts. The authors read deeply about traditional and modern shipbuilding methods and visited numerous shipyards, design agencies, and departments of naval architecture. They identified the major processes of ship design and construction as well as the main constituencies (customers, classification societies, contract designers, detail designers, planners, yard workers, etc.) Considerable effort was expended to determine what the main design decisions are, who makes them, and what their effect on producibility and automation are. The “build strategies” of important yards were determined and compared, and economic data highlighting potential savings were identified to the extent possible. Several key activities (structure, pipe, ventilation, measurement, and economic analysis) were studied in detail.

on the other hand, little effort was spent cataloging available automation technology. Not only are there several sources for such information, but it was the authors' opinion that shipbuilding will require specific developments and that much existing flexible automation used in manufacturing is not directly applicable in shipbuilding.

The authors learned a great deal about shipbuilding during the study and are aware of important differences between shipbuilding and manufacturing, including the great influence of planning. The need to integrate design, planning, and production merely reinforces the “system” aspect of shipyard automation and supports several conclusions below. In particular, white collar activities like planning and scheduling also need to be automated.

The authors are also aware of important differences between commercial and military ships. Compared to military ships, commercial ships are characterized by:

- relaxed design specifications
- less dense interiors and less complex technology

- more design and production stability
- more rationalized design and production
- relatively more cost in structure, less in outfitting

For the forseeable future, military ships will be the prime business for U.S. yards, but important lessons from commercial design and production methods have had and will continue to have relevance.

The authors are also aware of their limited knowledge of shipbuilding, especially in view of its complexity. Offsetting this, they hope, is their fresh approach as outsiders who may not be encumbered by habit or preconceptions.

C. Definitions

We define flexible automation as any automated or semi-automated process which is able to adapt or be rearranged to some degree to accommodate changing job configurations, sizes, times or other important conditions. This definition captures the requirement without presupposing any particular technology for meeting the requirement.

Although flexible automation usually implies robots, our definition purposely goes beyond this. TOO often it is assumed that robots can be substituted for people. Most of the time this strategy fails due to lack of understanding of what the people were doing. Our definition of flexible automation includes robots, process lanes and other reconfigurable machines, and is consistent with conclusions below that successful automation requires more process understanding and rationalization of design and planning than presently exists in U.S. shipyards.

Flexible automation is different from fixed automation, which usually is built specifically to be very efficient for doing a job automatically the same way again and again. Two classes of flexibility can be distinquished. They are gross and fine. Gross flexibility allows adaptation to new sizes or shapes of parts, for example, and is usually accomplished in software by loading a new control program into the machine. Fine flexibility allows the machine to accommodate minor variations in real time, such as a varying weld seam dimension, and is usually accomplished with sensors and real time control.

D. The Flexible Automation Challenge

The key to implementing automation successfully is to keep the machines busy. Since fixed automation is usually simpler and more efficient than flexible, it is often the best choice if thousands or millions of identical or nearly identical jobs must be done. The challenge to flexible automation is to make jobs similar enough so that they can be accomplished economically by a piece of flexible automation, utilizing its gross flexibility. If too few jobs are similar enough, the machine cannot be kept busy. E the jobs are not similar enough, the machine, in order to accommodate them, will be so complex and expensive that it will be slow, uneconomical, or unrealizable.

To meet this challenge, designers and engineers need to know how to encourage similarity between jobs. It is true that few if any shipyard jobs are identical in the usual manufacturing sense. Therefore, one must be prepared to redesign, to seek similarity, and to combine job steps now done manually and separately until a whole is created which is similar to others.

This will require a cooperative effort between planners, detail designers, and automation engineers. The philosophy of product-oriented shipbuilding is the key to this effort. The procedure will be iterative because its steps are interdependent. Figure I-1 depicts the interactions. Planners must recognize the capabilities of new automation equipment and identify similar jobs and interim products suitable for that equipment. Designers must recognize the interim product types that are easiest to build, and must design the ship’s modules and assemblies (structure, pipe, vent, foundations, etc.) to fit these types. Detail designers must optimize less and standardize more. Automation engineers must recognize the interim product types and their requirements, Planners

Recognize capability of automated equipment

Identify similar interim products and define ship modules of suit

Automation Engineers

Identify economically attractive interim products

Understand capabilities of technology

Design equipment and process lanes to accept job differences within each interim product class

Suggest design changes to expand classes of easy-to-make items

Designers

Recognize interim products

Design ship modules and parts to be easy-to-make interim products

Explain functional requirem-ments of products to planners and automation engineers

Figure I-1

Schematic of Interactions Between Planners, Designers, and Automation Engineers As They Focus Product- Oriented Ship Construction onto Flexible Automation Opportunities and design equipment to handle a range of similar jobs comprising a type of interim product. They can also recognize technical blockages to automation and suggest design changes.

Classification and coding will help identify similar jobs. A suitable code must capture the essential technical factors such as size, work type, work content, tolerances, and so on.

Even if no automated equipment is ever built, the long-term rationalization and codification process described above will lead to easier and lower-cost shipbuilding.

E . General Conclusions

Shipbuilding is an intensely complex activity. Ships take two to three years to build and often longer to design, requiring the efforts of thousands of people. There is heavy reliance on planning to coordinate all the activities. Competitive shipbuilding attacks this complexity systematically, almost scientifically, seeking to rationalize designs, simplify procedures, group similar tasks, and establish and maintain reasonable tolerances.

In U.S. shipyards, most activities are based on experience. Scheduling, outfit planning, bend and distortion allowances, to cite a few examples, are established manually. Although the experience base is strong, the scientific knowledge behind it is weak or missing, and this gap is not recognized. A firm science base would include cost and time data, measurement histories of process performance, and engineering models of the main fabrication and assembly processes. A science base has the advantage over an experience base of being easier to change while providing a firm basis for change.

While shipbuilding and manufacturing differ in many ways, they share at least one important attribute. If a design is simplified or a process streamlined, the product will cost less even if no automation is introduced . For this reason, we point

1. Among Japanese yards IHI seems to take this position most strongly, to the point of being proud of how few computers they have.

out that rationalization and automation opportunities extend well beyond fabrication in two generic areas:

- Planning, scheduling, unit and block definition, outfit sequencing, and other white collar activities.
- Measuring, data analysis, process improvement and similar manufacturing engineering areas.

Moreover, the greatest impact will be felt when fabrication and the above non-fabrication activities are integrated. Applying automation in isolated spots based on local cost savings will be less effective. It will be awkward to integrate with existing manual and non-rationalized methods, and it will miss the opportunity to redefine those methods and combine them with new technology effectively.

To be successful, flexible automation needs a suitable environment. This environment includes:

Good process models[2] that lead to clear specifications for machines.

Simple part shapes and subassembly designs that can be grouped by similarity and processed in flow lanes.

Awareness of measurement and tolerance issues by yard personnel.

Awareness of producibility issues by contract and detail designers as well as yard and shop planners.

The best opportunities for flexible automation arise from combining fabrication with design, information transfer, and material control. The process must be defined technically and

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2. A process model tells how process outputs (sizes, shapes, temperatures...) will change when we change process inputs (forces, times, voltages.....).

nomically, by design, so as to establish sensible shapes, sizes, and tolerances. It must be possible to define and predict work content and to predict both technical and economic performance--time, cost, dimensions, distortion. When flexible automation is integrated with design and planning, it will be easier to define work packages and enforce adherence to design specs and standards as well as fabrication tolerances and schedules. The capabilities of flexible automation may also inspire new designs or fabrication methods. Examples include weld heats or sequences, vent design, and division of pipe systems into pieces for shop fabrication. Better design and better fabrication encourage each other.

The cost and time savings that flow from such efforts will appear not only in shop activities where automation usually is applied, but also in outfitting, where there is much more saving potential. The same rationalization and redesign that benefit fabrication will, if properly applied, benefit outfitting. White collar activities (planning, design for zone construction, measurement, and process improvement) will all be stimulated. Furthermore, such activities can themselves be automated and may have to be in order to conquer their complexity.

F. Status of Automation in U.S. Yards Now

Design automation has been entering U.S. shipyards in the last 3 to 5 years, and the impact is only starting to be felt. Some yards have emphasized the engineering power of computers while others have exploited their ability to handle logistics of materials. Manufacturing industries, especially aircraft, are ahead in both categories plus in handling the logistics of information transfer.

Fabrication automation in U.S. shipyards is mostly confined to the first few processing steps on single workplaces. Nearly all cutting is automated, as is bending of pipe. The other steps (other bending, shape changing, measuring, and joining) are mainly manual and experience-based.

Both the planning and execution of outfitting are essentially manual with the exception of crane-lifts.

To extend automation beyond its present limits will require a better science base, simpler designs, and new fabrication and design concepts. Anyone familiar with manufactured parts is struck by the contrast with ship components. The latter are designed to be built up from raw stock. This results in many individual pieces, some extremely small. Many cuts, joints, and measurements are needed. Automation is difficult. New design and fabrication concepts are needed: current reliance on “cut apart and rejoin” needs to be replaced by “near net shape” to create the complex end items and to integrate the little pieces with larger ones.

A surprise to us is the degree to which shipyard operations are unpredictable or unpredicted. This is especially true of structural joining, where heat-induced distortion causes many parts essentially to be made twice. (The distortion problem is enhanced in recent frigates and destroyers because the plate thicknesses used are the most susceptible to distortion.) Much time is lost, and “completed” work is often passed to the next work area where its errors must be discovered and corrected. This distorts the concepts of “work station,” “completion,” ‘*work content”, and "time to do the work,” concepts which are fundamental to efficient production.” Inability to predict work output in shape, size, time or cost seriously inhibits automation. Identifying and correcting problems may take so long that automating the intended operation may not save much. The lack of accurate time and cost data also confuse any attempts to identify automation opportunities rationally.

Shipyards need better methods for gathering data, capturing costs, analyzing the data, and making decisions. Bath economic decisions (this operation costs too much) and technical decisions (this operation’s tolerances are too poor) are required.

The above discussion identifies problems without identifying who has the power to solve them. To address this, it is useful again to compare shipbuilding with manufacturing. The cost of manufacturing a product is determined mostly by its design, which implies materials, tolerances and manufacturing methods. In shipbuilding, the cost of production is determined both by design and by planning. The ability to affect these activities is shared by the customer, the design agents, and the yards, as indicated in Table I-1.

Table I-2 shows our qualitative assessment of how costs and opportunities are distributed.

Considering that planning has such a large effect on cost and that well-planned operations are easier to automate, it appears that the yards have quite a lot of opportunity in spite of any difficulties imposed by the customer.

Note, too, fiat time and cost for design and planning are a minuscule fraction of the life time and life cycle cost of a class of ships. Since one design activity and one planning activity per building yard determine the way 30 to 60 ships will be built, more time and effort on these influential topics could be well rewarded.

G. Future Patterns

Future economic and funding patterns are difficult to predict, but for the time being it appears that U.S. shipyards will do predominantly military work. An important fraction of that work will be repair, overhaul, and modernization. Furthermore, the ships to be modernized will be increasingly complex, and modernization will make them more so.

Table I-2 states that outfitting, dominated by installation and checkout of equipment and associated distributive systems, is the most costly and difficult phase of shipbuilding. Modernization will probably be mostly outfitting. For this reason, any efforts to rationalize and automate outfitting, including its planning, will have great future benefit.

H. Recommendations: Missions

In this section we discuss several long-range missions to enhance the climate for automation, based on the tables cited above.

MAIN ACTIVITIES			MAIN ISSUES AND ACTORS
COMPETING MISSIONS ALTERNATE TECHNOLOGIES INSTITUTIONAL ISSUES		BASIC SHIP PROPERTIES: MISSIONS, WEAPONS, PROPULSION, SIZE	TRADEOFF STUDIES SURVIVABILITY DEBATES OVER GOALS TECHNICAL RISK ASSESSMENT KNOWLEDGE GAPS DESIGN ACTORS CUSTOMER
BASIC SHIP PROPERTIES SPECS AND STANDARDS PRODUCIBILITY FACTORS SPACE ALLOCATION BUILD STRATEGY ZONE DESIGN	CONTRACT DESIGN DETAILED DESIGN PLANNING	MASTER BUILD SCHEDULE ZONE CONSTRUCTION PLAN MATERIAL ORDERS DRAWINGS	PRODUCIBILITY OF MAJOR ITEMS& DETAILS DESIGN-PLANNING INTERFACE SPACE ALLOCATION IN SHIP SPACE/TIME ALLOCATION IN YARD CREATION OF ZONES AND BUILD STRATEGY KNOWLEDGE GAPS: PLANNING ACTORS: CUSTOMER, CLASSIF SOCIETY, DESIGN AGENT, YARD
MASTER BUILD SCHEDULE MATERIAL DRAWINGS	SHOP DESIGN SHOP FAB	DETAILED PIANS AND FACILITY USE SCHED RAW PARTS SUBASSEMBUES PRE-OUTFIT MODULES	PROCESS UNDERSTANDING PROCESS AND ACCURACY CONTROL TOLERANCES AND MEASUREMENT DISTORTION AND REWORK ECONOMIC AND TECHNICAL DATA KNOWLEDGE GAPS PROCESSES AND CONTROL ACTORS YARD OR DESIGN AGENT
PRE-OUTFIT MODULES PARTS AND EQUIPMENT TEST SPECS	YARD FAB ASSEMBLY OUTFITTING TESTING	DELIVERED SHIP	CROWDING AND INTERFERENCE REWORK TESTING KNOWLEDGE GAPS: PLANNING, TEST, DIAGNOSIS, REWORK ACTORS: YARD, CUSTOMER

TABLE 1-1. SHIPBUILDING: MAIN ACTIVITIES, FLOW OF IDEAS AND OBJECTS, INTELLECTUAL PROBLEMS

	FAB OF COMPONENTS & ERECTION OF STRUCTURE	OTHER ASSEMBLY AND OUTFITTING	TREND OR OPPORTUNITY
COST CONTRIBUTION	SMALLER	BIGGER	FAB BIGGER OUTFIT SMALLER
AUTOMATION OPPORTUNITIES	BIGGER	SMALLER	FAB STILL BIGGER
COST INFLUENCES	DESIGN & PROCESSES	MANAGEMENT AND PLANNING	MANAGEMENT & PLANNING IMPACT DESIGN & PROCESS
RESPONSIBILITY FOR COST INFLUENCE	NAVSEA, ABS DESIGN AGENTS	SHIPYARD	YARDS TRY TO GAIN MORE INFLUENCE IN FAB

TABLE I-2

Table I-2 Qualitative assessment of how cost and opportunities are distributed

Customer Missions-

1. Extend previous efforts to involve yards during concept and contract design. TOO often we were told by customer design staff that they had no idea of yard fabrication methods. Without knowledge of producibility impacts, contract designers cannot contribute to lower costs and may in fact disrupt automation efforts.
2. Rethink specifications and tolerances. Changes in materials, joining and inspection methods, and increased ship complexity have run far ahead of many specs, which have not been thoroughly examined in years or decades. A promising step is an ongoing study of ventilation duct specs.
3. Create designs, standards, and funding incentives that encourage yards to rationalize shipbuilding. A negative example is the calculation of progress payments based on percent of structure completed. This formula discourages preoutfitting.
4. Establish a centralized mechanism for evaluating and approving process improvements, and certifying yards or vendors. The present situation of approving individual yards and/or individual ship classes produces inconsistent and contradictory results and interferes with creation of a critical mass of uniform methods.

Yard Missions-

1. Exert more control where they have it now, in detailed design, build strategy, planning, documentation, data gathering, analysis, and decision making based on data. Tremendous progress is possible through zone design and construction, grouping of similar jobs, detail design simplification, and process improvement.
2. Make the most of the options allowed by existing standards. This will require questioning existing

detailed design methods and habits.

3. Identify and thoroughly justify new design or fabrication options. Until or unless the customer establishes a centralized mechanism, it will be up to the yards to search other yards' or manufacturing and construction industries' methods, and learn how to adopt them.
4. Establish better cost capturing methods so that the total cost of performing jobs can be identified. In one yard, for example, only 40% of the cost of creating pipe pieces was charged to the pieces themselves.

Educator/Researcher Missions-

1. Make producibility a high priority. Tbo many naval architects see a ship as a thing to be designed rather than as a thing to be built and operated. (For example, of the SNAME publications listed in its 1986 catalog, none of 7 books, one (new last year) of 4 journals, 3 of 86 technical bulletins, and 2 of 13 national symposia deal with ship construction.) The naval architecture program at the University of Michigan is addressing this problem.
2. Identify the knowledge gaps and research needs of producibility as an intellectual area. The current amount of experience should not be allowed to mask the lack of a scientific knowledge base.
   To appreciate the gaps, one need only note the degree to which yards differ in basic matters such as when to blast and prime structural assemblies or what shape those modules should be.

Common to the above missions are two main themes:

1. The need to get better visibility into current practices--designs, costs, times, tolerances, errors--so that

genuine knowledge gaps can be identified and rational solutions proposed, tested, and implemented.

The need to couple design, planning, and production together more tightly.

I. Recommendations: Specific Implementations

The following specific implementation strategy is recommended:

1. The ongoing and successful adaptation and adoption of zone design and construction should be used as the basis for implementing flexible automation. Automation requires some changes in design philosophy, and the zone approach has already inspired new thinking. Three areas should be exploited, namely the concept of the interim product, the identification of similar "problem areas,"[3] and the use of classification and coding to capture similar interim products. The obvious strategy is to configure the automation to solve the common "problem," but implementing this goal will require considerable effort and ingenuity. We summarize the above discussion with the following recommendation:

2. Identify interim products with similar-enough problems. Design them to make the problems as simple as possible. Obtain time, cost, and tolerance data on current methods, and write process specifications. Search for alternate designs or processes to increase the similarity of jobs.

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3. "Problem area" is defined as the set of tools, methods and skills needed to do a particular kind of job. This set essentially defines the job.

3. There remains the question of prioritizing automation opportunities. Several criteria have emerged from the study, all worthy of consideration. They are:

a) Cost
b) rework
c) errors or statistical evidence that the process *is* out of control.
d) statistical evidence that the process is in control and thus well enough understood to permit automation.
e) danger, strain, pollution, poison resulting from human proximity to the work.
f) synergisms of design, material handling, and information handling.
g) mutually supportive time phasing, where the first automated step provides high quality interim products that make the next step feasible to automate.

To implement any of these criteria will require development of algorithms and computer aids for prioritizing and selecting opportunities.

Promising areas that meet one or more of these criteria are:

structural details
structural joints
pipe assemblies
vent assemblies
foundations
measurements associated with structural or pipe assembly or with outfitting.

The logic of this implementation strategy is laid out in Figure 1.2.

J. Organization of the Report

The body of the report is organized as follows:

Section II is a brief introduction which describes the study's motivation and methodology.

Section III asserts the system nature of the flexible automation problem and argues that the whole process of design, planning, and production influences and is influenced by flexible automation.

Section IV describes the study’s main results and findings.

Section V and VI present the technical and economic environment of shipbuilding as it affects automation opportunities.

Sections VII through XI deal with specific target areas: structure, pipe, ventilation, and economic modeling.

Section XII categorizes possible topics for future SP-10 projects according to the basic implementation logic. This logic emphasizes process understanding, proper design, zone construction concepts, and focussed technology.

Section XIII lists open questions for further research, while Section XIV contains the conclusions, recommendations, and implementation plan.

OVERALL FLEXIBLE AUTOMATION LOGIC

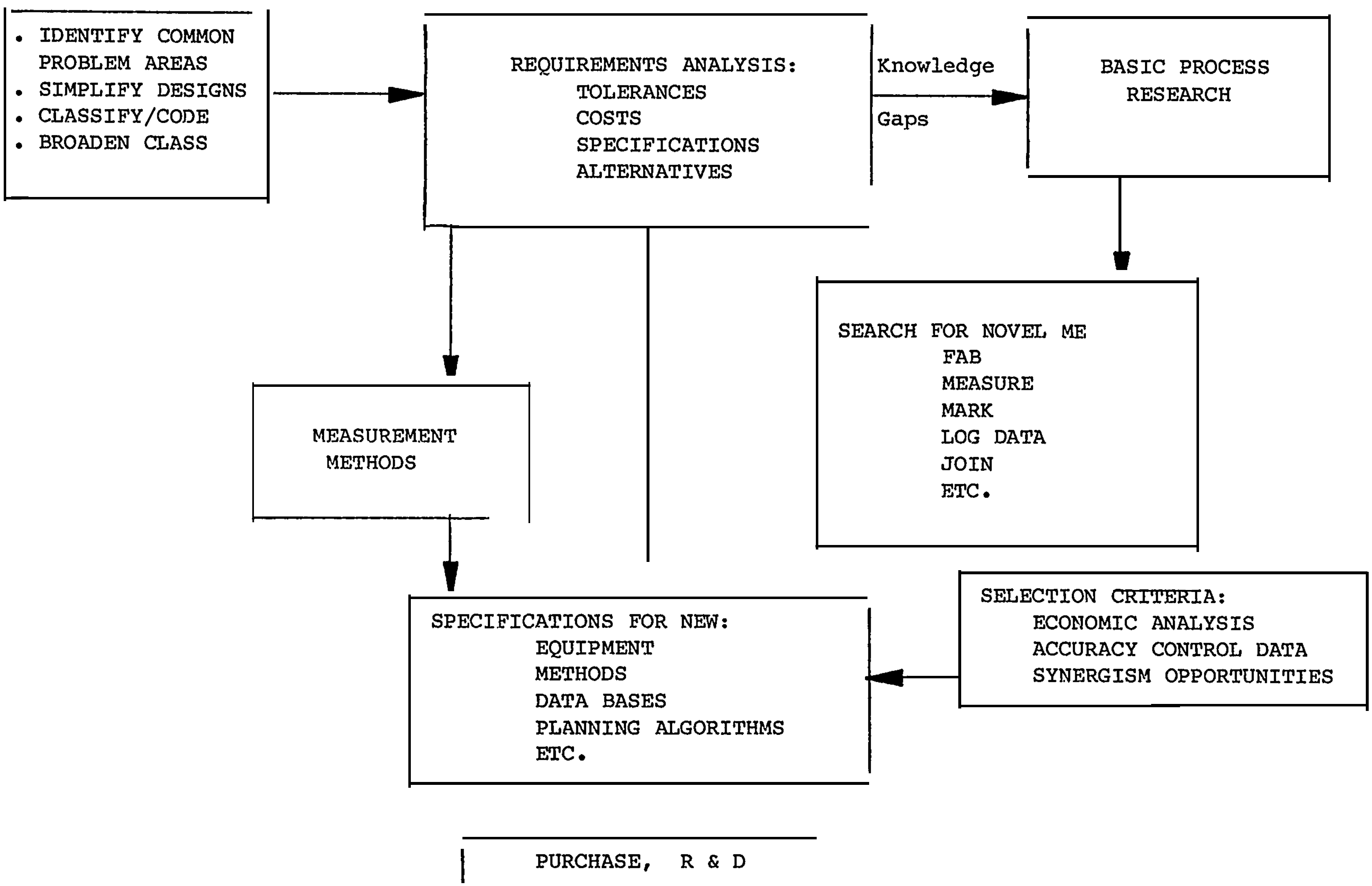


Figure I.2: The logic of the implementation strategy for Flexible Automation

11. INTRODUCTION

A. Background

The Flexible Automation subcommittee, SP-10, of the Ship Production Committee has commissioned the Charles Stark Draper Laboratory to apply its experience in industrial automation and robotics to flexible automation in shipyards. Our background in automation research, development, applications, and consulting with industry have allowed us to develop a methodology for studying products and manufacturing processes to see if they are suitable or ready for automation. While flexible automation usually brings to mind robots, our approach is to let the technical and economic constraints dictate the requirements, which may lead to our recommending any mix of

- product redesign
- rationalization and standardization of processes
- increased attention to tolerances
- an economically rational mix of people, robots, and other machines
- coordinated automation of design, fabrication, information handling, assembly and inspection

The method involves an in-depth study of the processes, including interviews with designers, planners, and direct labor. While shipyards differ in some important ways from our typical manufacturing clients, we have been applying the method essentially unchanged.

The ability to automate a process usually relies on answers to other crucial questions:

- is the process well understood, standardized, and repeatable?
- are the parts designed to be made and joined easily?
- are the tolerances, materials and other requirements known and capable of being met?
- are performance, cost, and producibility rationally balanced in the design?

Since these are attributes of efficient, high quality, producible designs, a study of automation possibilities exposes ways to improve designs and processes. Since these attributes make automation feasible, an automation study has to encompass these broader issues.

Our study is necessarily limited in time and scope, so its main impact is expected to be in increasing awareness among the yards and their main customer, the U.S. Navy, of the main issues. These are expected to be:

1. An agenda -- available time and cost data indicate that the most impact will be gained from improving the planning of fabrication and outfitting, and from rationalizing and better understanding the design and fabrication processes of structure, pipe, and vent.

2. The mutual impacts and leverage points -- the shipyards control the planning of their operations but their facilities sometimes prevent their using the best methods. However, contract design agents and the customer control major design parameters and have funds for obtaining more process knowledge. Design can affect costs greatly in both fabrication and outfitting.

3. The need for rationalization -- rationalization is the process of defining designs and methods based on balanced consideration of competing performance and cost requirements. Rationalization of the construction of today's naval,ships is limited by too much emphasis on performance, too little understanding of processes, and too narrow consideration of design alternatives. It *is* not limited by lack of basic technology, although there is a lack of specifications for designing appropriate equipment.

4. The prerequisites -- automation flourishes in an environment characterized by producible designs, standardized processes, awareness of tolerances and true costs, and recognition, encouragement, and exploitation of similarity and simplicity of jobs. U.S. shipyards do not present this environment broadly enough.

5. <u>The expectations</u> -- ships will never be built by long lines of robots, but neither do they need to continue to be hand-built like decorated cakes. Until the requirements of tasks are known and specifications for automation can be written, there will be little progress except in a few isolated islands where existing industrial robots coincidentally fit in.

6. <u>The leverage</u> -- more automation opportunities will follow better understanding of the fabrication and planning processes of shipbuilding. The increased understanding will be a valuable reward in itself, possibly of more value than the automation it may foster.

B. Methodology

The study method consisted of extensive yard visits, background reading, consultation with teachers of Naval Architecture and U.S. Navy and design agent personnel familiar with design, and in-depth studies of the design and process steps of some sample parts of ships. We identified the following areas for deeper study:

structure

pipe

vent

welding

jigging and fixturing

measurement methods (in fabrication and outfitting)

An important lesson we bring from our previous work is that only rarely can a process or product by automated without changing its design or the manual methods of making it. In the case of ships, much of our study effort went into finding out the reasons why parts are designed and made as they are. Due to the many constituencies, such as registration boards and designers, plus the inherent soft points in ship design methods and the complexity of naval ships, it can be quite difficult to track down these reasons. But the effort is going to be worth it. Once we identify those features that lead to high cost or that impede automation, we can prepare a case for alternatives.

To aid the identification process, we defined and employed the following shipyard visit strategy. We begin with a general tour, and then focus on a particular system, such as structure. We then successively visit the designers, the yard planners, the shop planners, the shop, the erection areas, the ways (if any), the structural blocks or modules, and finally the ship. As time allows, we repeat this for other systems.

We try to find out where decisions are made that affect build sequences, unit sizes, joint locations, tolerances, extra process steps, cramped work sites, interrupted geometries, irregular or novel shapes, and other factors that affect automatability. We also try to find out the extent to which requirements are known and/or adhered to, as well as how much success has been attained in achieving the goals of zone construction.

Because of the impact of design decisions on producibility, we have also visited Navy and civilian design agents and consulted with ship design authorities.

Finally, the study team has made in-depth case studies of a few items to show in detail the steps needed to determine the requirements for an automation project.

It is important to distinguish this approach from that often taken by automation or robotics consultants. Typically their attention is focussed on a particular technology in an attempt to see how it might be applied to current operations. This is often a fruitless exercise because new technology is not compatible with old methods. The old methods are based on old capabilities, usually people, that have certain strengths and weaknesses which bear no relation to the strengths and weaknesses of new machines. New combinations and arrangements of jobs, new joining methods on relocated boundaries, or new shapes and materials are examples of the differences that new technology affords or demands. The changes are usually profound, and require new designs, new design methods, new kinds of material handling and information transfer, etc. For this reason, true change and dramatic increases in productivity usually cannot occur simply by substituting a machine for a person in an existing process. Broad and deep study of all the phases of manufacturing are needed.

III. FLEXIBLE AUTOMATION IS A SYSTEM PROBLEM

Flexible automation can be defined as any automation that is capable of improving productivity in the presence of differences between jobs. This definition captures the requirement without committing to any particular kind of solution. We emphasize this because flexible automation is often identified with robots, which do not cover the range of possibilities. In this section, we discuss the requirements in order to provide a framework in which to give our findings. These requirements fall into two groups: technical feasibility and economic feasibility.

To attain both kinds of feasibility, several conditions must be met.

Design feasibility: simplicity, attainable tolerances, easy jigging, physical access

Production quantity: enough work to keep the machines busy, achieved by sheer number of similar jobs, or by identifying problem areas[1] and planning the ship's design and fabrication to emphasize feasible problem areas, to be executed on process lanes

Automation feasibility: the process is well enough understood that specifications for fabrication and measuring machines can be written, so that output work meets specs and tolerances

Availability of data: both technical data (sizes and shapes) and economic data (times and costs) must be known to permit rational decisions to be made

1 A problem area is a set of materials, tools, processes and skills. This set defines a class of job in the IHI-Chirillo terminology. [Ref 1]

Design or production stability: the persistence of a certain mix of problem areas over enough time so that designers and fabricators learn to deal with them efficiently

Manufacturing data feedback: systematic capturing of times, costs, and physical measurements to permit trends to be recognized and processes improved

This list comprises many areas of shipbuilding outside of fabrication and leads to the conclusion that successful flexible automation depends on improvement throughout shipbuilding. The range of activities that affect automation include those controlled by the customer, the contract and detail designers, and the fabricators. Since automation and its companion “producibility” are not ends in themselves, a lot of tradeoffs must be considered. It is our opinion that improving the feasibility of automation will improve the quality of ships and the efficiency of their construction even if no specific flexible automation equipment is ever utilized. These feasibility requirements are discussed in more detail in the remainder of this section. In the next section, we will compare the requirements to the current state of U.S. shipbuilding.

A. Technical Feasibility

The first thing we look for when considering the automation of a task or process is technical feasibility. Some important blockages to technical feasibility are listed in Table III-1, along with examples. Resolution of these problems may be found in better design rationalization and better process understanding. It is true for manufactured products, and likely true for shipbuilding, that much of a products cost is determined when it is designed. Choices of materials, tolerances, joint locations, joining methods, part sizes and shapes, and joint density (joints per length or weight) are among those that matter. A rationalized

TABLE III-1 TECHNICAL FEASIBILITY BLOCKAGES

Blockage	Example	Effect	Remedy
Poor design of parts	Structural details	Too many little pieces. Must be held by 2 hands in awkward places. Interrupt geometry of plates and beams.	Redesign
Process not understood	Structural shrinkage or distortion	Cannot predict outcome. Creates need to measure and recut. Automation, if any, needs constant adjustment.	R & D needed
Process not standardized	Weld sequence	Results not repeatable. Statistics not valid.	Systematic controlled experiments. Adoption of standard.
Work not similar enough over time	Pipe or vent fab	Special setups needed for every job.	Redesign parts. Rearrange work. Redefine work units.
Too many interruptions	Time, space, geometry procedure	only a little work gets done before a change or stop needed. Dilutes impact of automation.	Simplify parts. Clean up geometries.

design is one in which such choices are made with due consideration for producibility as well as performance. Processes that lack sufficient understanding include welding, weld sequences, tolerances and error growth prediction in structure, and the logic of planning outfitting and deciding module definition. Shipts parts whose design requirements or function are not well enough understood include vent duct (materials, fab methods, wall thickness) and structural details (shapes, location, effectiveness).

B. Economic Feasibility

Presuming that a task's automation is technically feasible, the economic feasibility must also be assured. This is often difficult. Conventional economic justification methods are based on an array of assumptions and required data. The assumptions do not necessarily apply to shipbuilding in the U.S., given the industry's current structure and its relation to its main customer. Furthermore, the required data may not be available. Ideally, one must know the current cost of doing the work that the equipment would do. This information is often lacking, due to poor record keeping, poor process definition, or combining several preparatory *or* repair work steps. Current wasteful actions such as adjusting or fitting are assumed to be part of the regular cost of doing the job and are institutionalized in standard times. lt is therefore not realized that much more could be saved.

Another difficulty is that economic analyses often assume that the design is the same, whereas redesign offers new economic alternatives. For example, pipe spools made by automation might be cheaper if they had more sleeve joints and fewer butt joints than current designs. More will be said about economic justification strategies below.

C. Fixed Versus Flexible Automation

We defined flexible automation above as any automation that can adapt to changing job conditions. This distinguishes flexible from fixed automation, which usually is built specifically to be very efficient for doing a job automatically the same way again and again. TWO classes of flexibility can be distinguished. They are gross and fine. Gross flexibility allows adaptation to new sizes or shapes of parts, for example, and is usually accomplished in software by loading a new control program into the machine. Fine flexibility allows the machine to accommodate minor variations in real time, such as a varying weld seam dimension. This flexibility is usually accomplished with sensors and real time control modifications to the program.

The key to implementing automation successfully is to keep the machines busy. Since fixed automation is usually simpler and more efficient than flexible, it is often the best choice if thousands or millions of identical or nearly identical jobs must be done. For flexible automation to be successful it is necessary to make jobs similar enough so that they can be accomplished by a piece of flexible automation, utilizing its gross flexibility. If too few jobs are similar enough, the machine cannot be kept busy. If the jobs are not similar enough, the machine, in order to accommodate them, will be so complex and expensive that it will be slow, uneconomical, or unreliable.

If flexible automation is to succeed in shipbuilding, designers and engineers need to know how to encourage similarity between jobs. It is true that few if any shipyard jobs are identical in the usual manufacturing sense. It is unlikely that any progress in design rationalization or process understanding will change this. Therefore, one must be prepared to seek similarity and combine job steps now done manually and separately until a whole is created which is similar to others.

This will require a cooperative effort between planners, detail designers, and automation engineers. The philosophy of product-oriented shipbuilding[ref. 1] is the key to this effort. The procedure will be iterative because its steps are interdependent. Planners must recognize the capabilities of new automation equipment and identify similar jobs and interim products suitable for that equipment. Designers must recognize the interim product types that are easiest to build, and must design the ship's modules and assemblies (structure, pipe, vent, foundations, etc.) to fit these types. Detail designers must optimize less and standardize more. Automation engineers must recognize the interim product types and their requirements, and design equipment to handle a range of similar jobs comprising a type of interim product. They can also recognize technical blockages to automation and suggest design changes. Classification and coding will help identify similar jobs. A suitable code must capture the essential technical factors such as size, work type, work content, tolerances, and so on. Figure III-1 depicts these interactions.

Specifications and standards are not blockages to such an activity. There is a need for creative designs and building strategies that exploit opportunities for combining new designs, similar jobs, and automation. We found no evidence of an organized, focussed effort of this type at any yard or design agency we visited, although pieces of the effort were observed.

D. Creating Specifications

until an operation is well understood, we cannot write the specifications for a rational design or for equipment that would be technically and economically feasible. Nor can we utilize equipment, such as robots, that are available for manufacturing industry, because these items have been designed based on quite different criteria. The parts they deal with are smaller and the amount of work done on each is typically less than on ship parts. Generally, work is brought to them, which is impractical for large ship pieces. Where there are exceptions to this, such as in pipe and vent fabrication, there is not yet enough uniformity of shape, ease of joining method, or quick and accurate jigging methods to permit current equipment to deal with them.

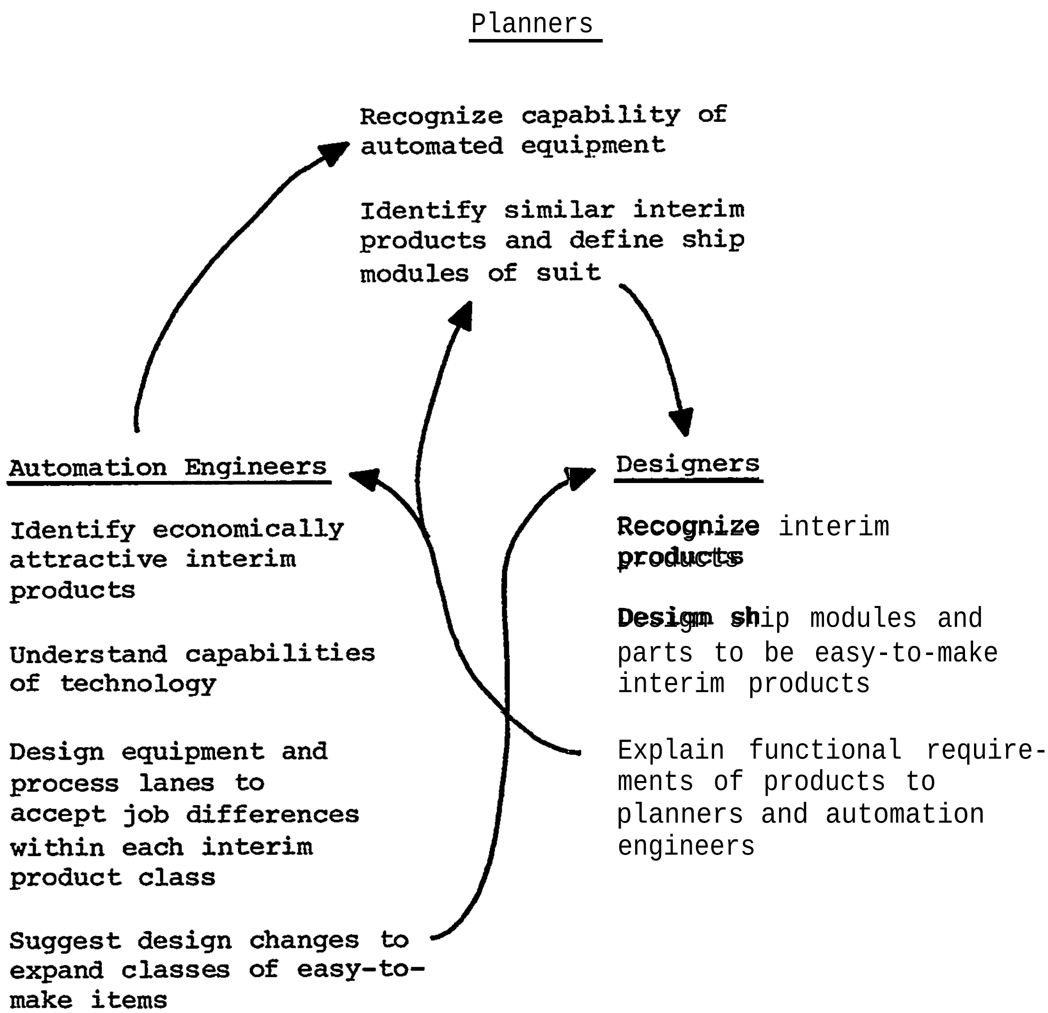


Figure III-1
Schematic of Interactions Between Planners, Designers, and Automation Engineers As They Focus Product-Oriented Ship Construction onto Flexible Automation Opportunities

The world of manufacturing is ahead of shipbuilding in amassing an understanding of job requirements. An important issue is that the user industries, rather than the automation vendors, have been the source of much of this understanding, or have been the source of funds for obtaining it. Given that shipbuilding represents a smaller market for such equipment, it is likely that again the users will have to be the source.

E. Organizing the Work

Once the individual job steps are understood, there remains the task of creating a rational task sequence that supports high quality, efficient manufacture. Choice of operation sequence affects many important topics, as outlined in Table III-2.

F. Summary

This Section discussed requirements for flexible automation and showed that all aspects of shipbuilding contribute to its success. A strategy for focussing effort on automation begins with the concept of the interim product as a way of creating a group of similar jobs. The challenge is to make the group economically large enough without making it too diverse technically. An iterative and cooperative effort involving planners, designers, and automation engineers is needed.

The next section describes shipbuilding in the United States as we have seen it and discusses the extent to which it is ready for flexible automation.

TABLE 111-2 EFFECTS OF OPERATION SEQUENCE

Topic	Poor Sequence	Good Sequence
Handling	Requires many turnovers or adjustments. Makes trades leave and return	Few turnovers - trades stay on until all work is done
Tolerances	Errors grow	Error growth is controlled
Task Definition	Operations broken up or separated in time	Operations of one type are sustained at one place. Jobs of one type are repeated. Job units requiring one setup or setup type are repeated.
Interference	Trades conflict	Trades coordinate
Concentrate on by workers	Jobs are interrupted Jobs change character	Jobs are regular and repeat their characteristics.

References

1. Chirillo, L.D., Product Oriented Work Breakdown Structure. Published by the U.S. Maritime Administration as part of the National shipbuilding Research Program.

Iv. OVERVIEW OF THE STUDY'S RESULTS

A. Cost Distributions

Since cost is the driver, we consider first the available data on naval ship acquisition cost.(l,8) figure IV.1 shows that labor - which is directly affected by automation - is a small fraction of total acquisition cost. Automation indirectly affects materials costs through reduction of waste, but this will be even a smaller fraction.

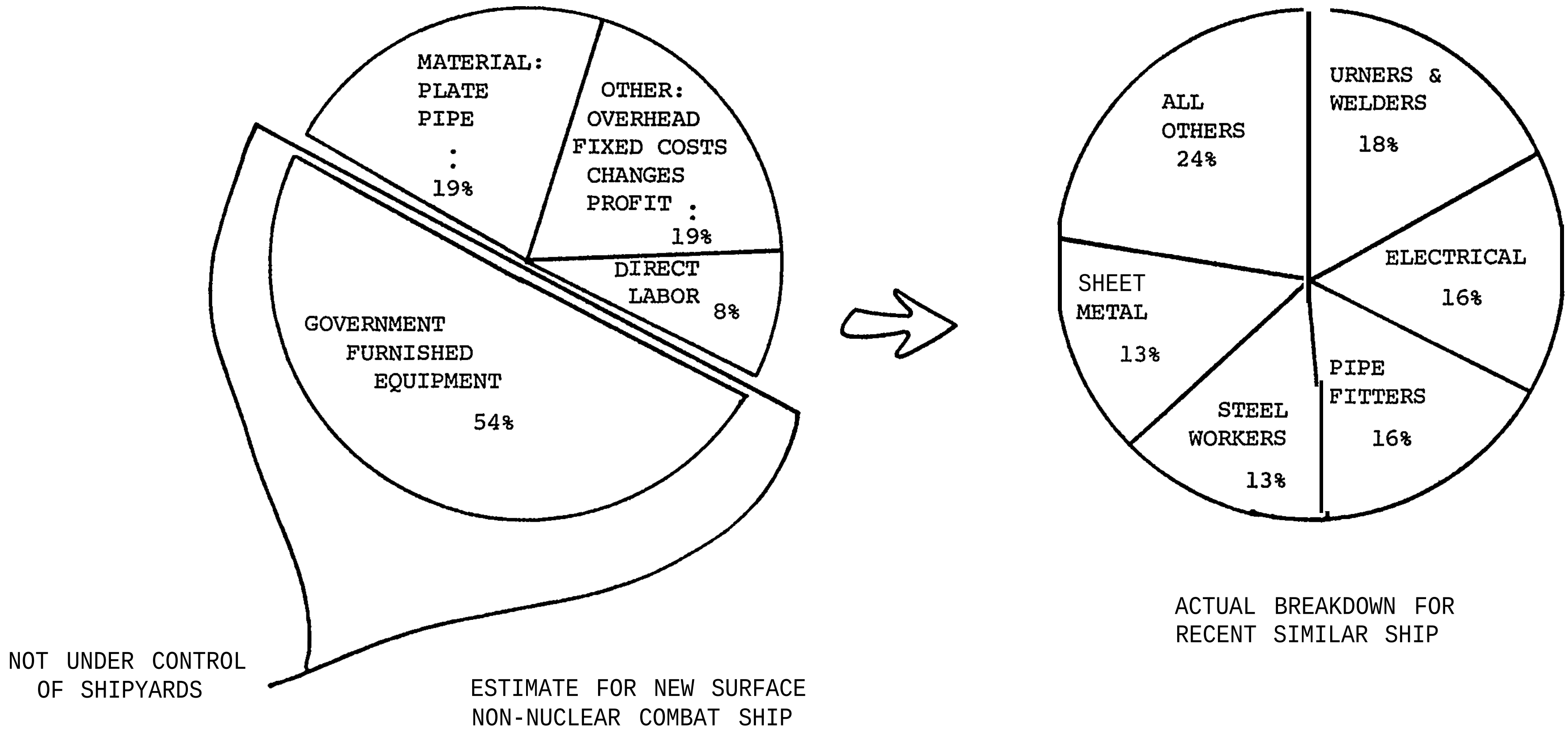
While labor saving means labor elimination in some cases, it also means better labor utilization. Figure lV.2 shows that a person may spend his time well or wastefully. Too little is known about the distributions here. The shipyards have the opportunity to find out the "true costs" and plan improvements accordingly.

The available data (Figure IV.1) indicate that four trades dominate the costs. Electrical workers are concentrated in outfitting, while the others are occupied in both fabrication and outfitting. In the latter they work in very crowded conditions. There is anecdotal evidence that a time penalty of 2 to 10 times is incurred when a job is done on board instead of in the shop, but we have located no systematic studies of this. Some specific but fragmentary data are analyzed in the sections on Pipe and Vent Systems.

These data lead to the conclusion that the work these trades perform -- structure, pipe, vent, plus the attendant jigging, measuring, and joining processes -- should be the focus of automation studies.

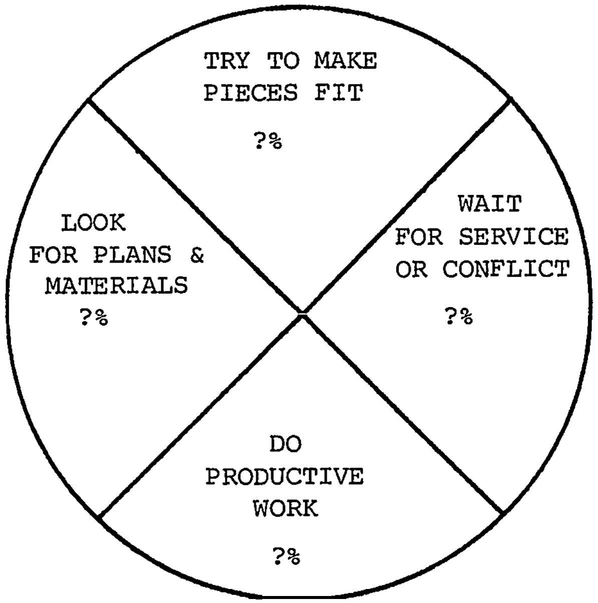
B. Comparison Between Manufacturing and Shipbuilding

Compared to manufactured products, ships are built from more raw materials and fewer purchased subassemblies. Ships are made with fewer types of raw materials and joining methods. There is more hand work, more tiny pieces, more built-up shapes, and fewer cast, stamped *or* molded pieces. Workstations have more workers at them but only one or two trades are represented. The actual work



MATERIAL:
PLATE
PIPE
:
19%
OTHER:
OVERHEAD
FIXED COSTS
CHANGES
PROFIT
:
19%
DIRECT
LABOR
8%
GOVERNMENT
FURNISHED
EQUIPMENT
54%
NOT UNDER CONTROL
OF SHIPYARDS
ESTIMATE FOR NEW SURFACE
NON-NUCLEAR COMBAT SHIP
ALL
OTHERS
24%
URNERS &
WELDERS
18%
ELECTRICAL
16%
SHEET
METAL
13%
STEEL
WORKERS
13%
PIPE
FITTERS
16%
ACTUAL BREAKDOWN FOR
RECENT SIMILAR SHIP

FIGURE IV-1



DO WORKERS SPEND THEIR TIME?

FIGURE IV-2

of sizing and joining we pieces is a smaller percentage of a person's time, with more percentage spent collecting plans, tools and materials, measuring, fitting, cutting, and otherwise preparing to do what in manufacturing would be the actual work.

Any attempt to make shipbuilding more like manufacturing must address these differences. The next few subsections discuss specifics.

C. Major Automation and Productivity Blockages

We have identified several major blockages to automation and improved productivity in shipyards. Some of these are widely recognized, others less so:

1. Difficulty of predicting the size and shape of major pieces and subassemblies. If a structural unit 80 feet long is to be made to 0.25 inch tolerance, the ratio of tolerance to length is 0.00026. Since most typical manufacturing works to a ratio of about 0.001, shipbuilders are aspiring to a high standard of precision. Temperature adds to the difficulty: a rise of 15 degrees C will add 0.144 inch to the 80 feet.
2. Lack of understanding of processes and the influence of process variations on part size, design alternatives, and ability to write specifications for automation equipment. The main process in ship structural work is welding. While it appears cheaper than riveting and offers many design options excluded by riveting, it brings huge baggage of its own in terms of metallurgical changes in metal, locked-in stresses, crack growth opportunities, and heat-induced distortions. These force additional safety allowances to be prescribed in designs and cause much of the dimensional uncertainty. (An unfortunate coincidence is that the 3/8" plate common on modern destroyers is much more subject to distortion than either thicker or thinner plate[2].) Increased understanding of welding is needed in terms of shrinkage prediction, distortion minimization, weld sequences that preserve

shape and size, weld-primer compatibility, one side welding, and so on, before widespread automation of joining can proceed. The Japanese effort in accuracy control is a sophisticated attack on these problems. It is more than mere data taking, because it encompasses careful experiments and analyses to determine part shapes plus weld and erection sequences that minimize error propagation.

3. Lack of rationalization of the design process and lack of appreciation of the influence of design changes on process simplification, part count, methods alternatives, and other cost impacts. The shipyards control only part of the design process, since many design decisions are made by distant designers who are not aware of producibility issues. Yet many design decisions that affect automatibility are made by lead yards when they determine structural details and the shape and size of pipe and vent pieces. These items in particular require much hand-work, are odd shapes, and are sometimes not designed at all but made to fit. There is too great a tendency to design things so that they require cutting raw material down to the smallest possible pieces only to weld them all back together again. This is particularly striking in tripping brackets, collars, and gore-ell vents. Figure IV-3 contains some suggestions aimed at reducing the number of separate pieces, preserving relative position of parts from cutout to final installation, and reducing the need for multiple hands or jigs to hold pieces during installation. In the case of structural details, it may not be possible to decide at present if these or other suggestions are acceptable. We could not find anyone who could tell us concisely what function some details are really supposed to fill. This is a fatal gap since, at a minimum, a new design must perform the required function.

4. General lack of awareness by yard personnel of the importance of standards, process uniformity, tolerances, and advanced methods. We find shipyard managers, designers and supervisors too little informed about such things as process requirements (can

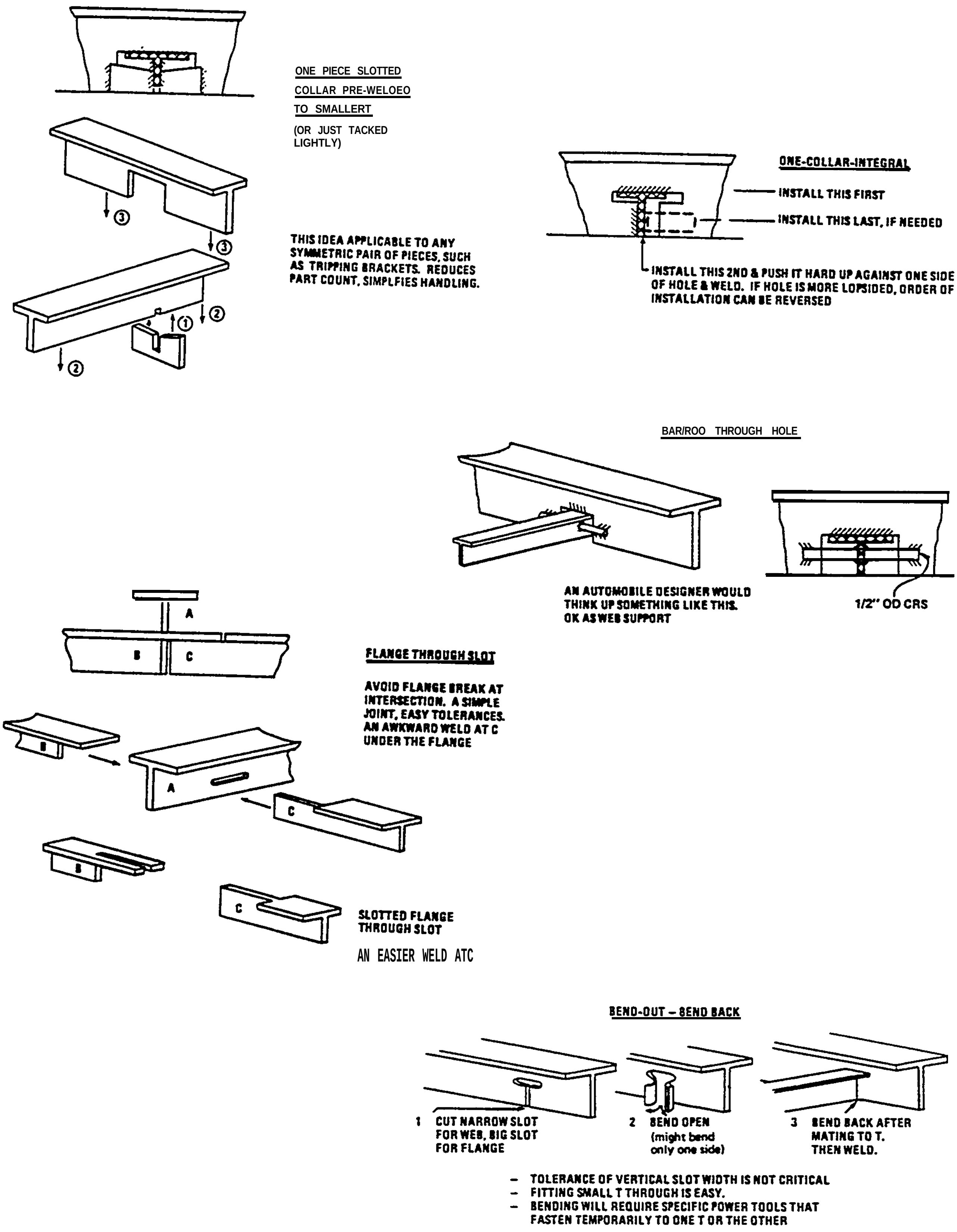


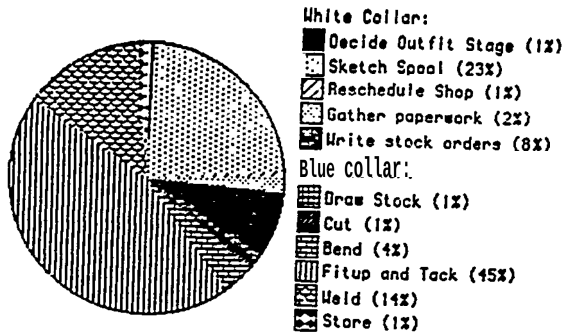
Figure IV. 3: Several Suggestions for More Producible Structural Intersections or may primer be welded through or not), tolerances (in one yard we visited, pipe spool tolerances were variously quoted at anywhere between one sixteenth and one quarter inch), whether a particular method is possible (such as avoiding collars by cutting T-shaped reeving slots for stiffeners to pass through, which is "impossible" at one yard and done routinely at another), and especially, what is the best technology and best method known or available. This lack of information seriously blocks the introduction of automation, which requires a lot of attention to standard methods, tolerances, and process understanding. If the prerequisites are not appreciated, efforts to automate will fail, the equipment will be blamed, and the effort will be abandoned.

5. General lack of awareness by designers of the cost impact of seemingly small design decisions. A recent study(3) of structural details listed about a dozen variations of each type, varying in work content from 0.6 man-hours to 2.6 man-hours, a ratio of 433%. An LNG tanker has 54480 details, comprising 107440 total man-hours. The number of details varies with the square of the number of stiffeners and structural intersections. More examples are given below.

6. Lack of accurate, detailed cost data. We cite here three examples from pipe shop work.

a) A yard's assistant pipe shop foreman listed the cost centers, charge numbers, and approximate man hours associated with his shop's operations, starting with breaking a system drawing into spools and ending with palletizing finished pieces for delivery to the installation site. Figure IV.4 shows the balance of "white collar" and "blue collar" work. It also shows how little of the cost can actually be traced to the pipe piece itself. The rest is either charged to the ship or to the shop. Some is charged to the welding shop. This makes it impossible to trace total pipe costs, because welding's share is lumped into costs for welding other things, like vent and structure.

b) If we combine typical quotes for man-hours per spool (say 5,



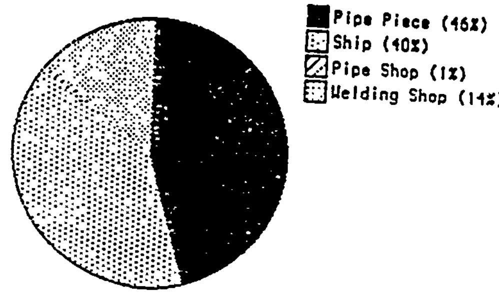


Figure IV-4

a) White collar work associated with pipe fabrication is about 35%, while blue collar work is 65% of the estimated cost per pipe piece.

b) 46% of the fabrication cost per pipe piece (white collar plus blue collar) is charged to the piece itself. The rest is allocated or charged elsewhere.

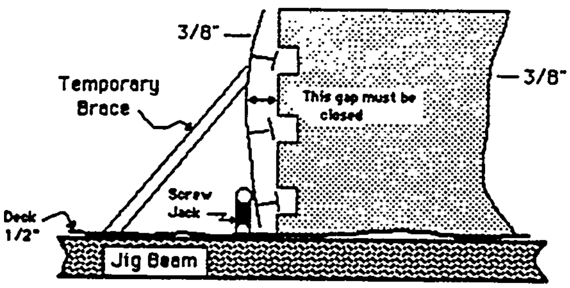


Figure IV-5
Example of Actual Structural Fitup Difficulties Caused by Distortion

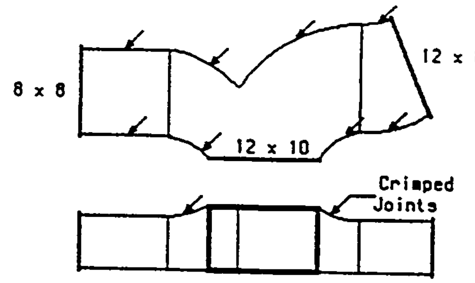


Figure IV-6
Example of Commercial Vent (0.025" Galvanized Steel) with Out-of-Plane Crimped Joints

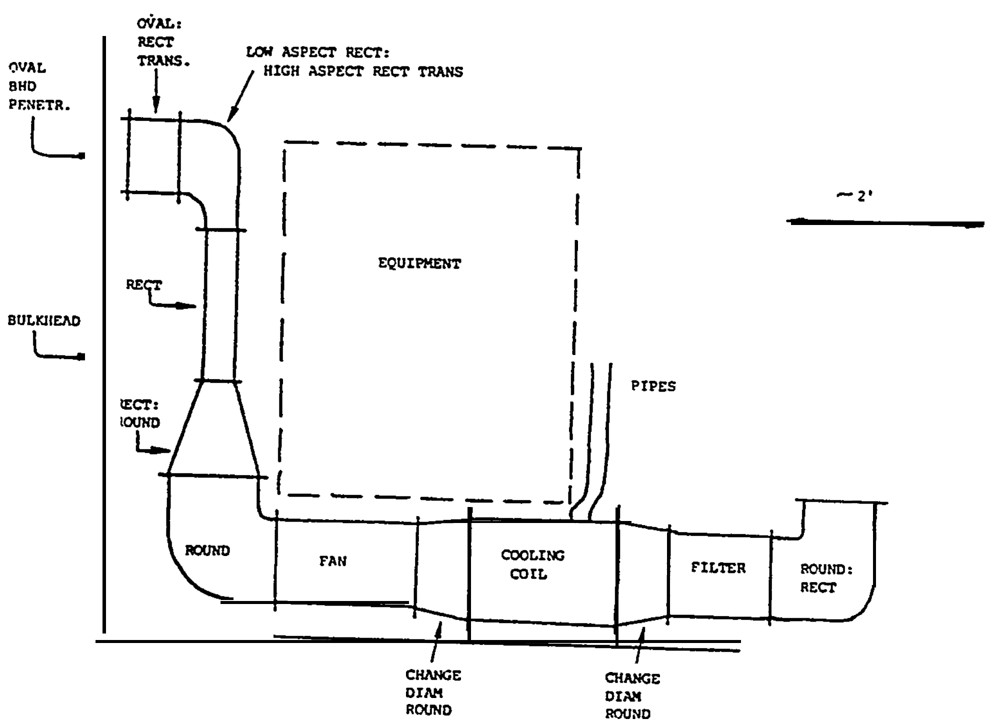


Figure IV.7: Typical Vent Design in Crowded Fan Room for example) with the number of shop-made spools on an FFG-7 class ship (around 10000), we find that we can account for about 69000 man-hours. Typical total pipe shop charges (excluding welding) for an FFG exceed 250,000 man-hours. This means that the above figure for pipe fabrication accounts for a very small fraction of the total charges. How is the remaining time spent? The candidates are installation, templating, ship-made runs of small pipe (20000 feet on an FFG) and unproductive time. For example, data from a recent destroyer show that, for over 100 pipe work packages, installation man-hours were 3 to 11 times more than fabrication man-hours for the same pipe pieces, depending on the system. The data cover 54% of pipe fab and install time by all trades on this ship. Firemains had the highest ratio. (On the same ship, data for ventilation are less extensive but show that for 10 job orders the ratio of installation to fab time averages 2.8:1. The data cover 39.5% of vent fab and install charges by all trades.)

c) Comparison of data from four different yards on “blue collar” time to fabricate an average pipe spool reveal wide diversity. We do not know the reason for this. However, it is common in manufacturing for the most productive company in an industry to be very much more productive than the least.

Yard	Automation in Shop	Estimated Man-Hours/Average Spool
A	Extensive	3
B	Yard A with only a Bender	9
C	Bender	8? (no actual data available)
D	Bender	4.7
E	Bender	5.5

7. Lack of awareness of the need for a better knowledge base. At various places in this report, we refer to the lack of an adequate knowledge base in areas such as predicting structural module shape or planning ouffit sequences. These activities are currently performed by yard personnel with years of experience. It is important to realize the difference between experience and scientific knowledge. The former is hard to transfer to others, is difficult to standardize, and may become worthless if some circumstances, methods, or materials change. Yet, because the experience exists, the lack of scientific knowledge may not be recognized.

8. Lack of a centralized agency in the Navy for certifying new automation processes and accompanying new designs, methods or materials. The ABS has a research division that deals with such matters, and this, together with the relative simplicity and relaxed standards in non-combat ships, makes such ships easier to build. The Navy's approval system is distributed throughout the yards via the Supships organization and the type desks. This fragments efforts to automate, creates inconsistencies from yard to yard or class to class, and prevents a critical mass from accumulating that would make some new methods economical.

D. Specific Focus Areas

We next discuss specific findings in the focus areas of structure, pipe and vent.

1. Structure

In structural shops, automation is confined to cutting out the pieces, plus preblasting and priming. Automation of structural fabrication and assembly is limited by:

a) inability to predict resulting sizes

b) too much distortion, requiring wasteful time spent straightening, so that automatable joining time is a small fraction (see Figure IV.5)

c) too little machinery used in attaching stiffeners, resulting in too much hand work, not enough spacing accuracy, and lost opportunity to automate the longest welds in the ship

d) too little process uniformity in joining or erecting, causing unpredictable distortions and process times

e) too little grouping of operations into wholes with a large quantity of like work. A potential opportunity is welding grillages of stiffeners to shell or deck plate. This is currently done one beam at a time, with many small pieces attached manually. The whole flavor of this operation would have to change. The contours of each box bounded by four beams would have to be made as clean and simple as possible, including finding alternate ways to do what the little pieces do. Then a "box weld" operation could be defined and a variety of mechanisms, simple or complex, could be considered for automating the welding. This operation would comprise the same steps again and again, differing only in the exact dimensions. Design or tolerance differences could be accommodated by sensory feedback, as long as the pattern is the same. In numerical control, the analogous operation is called pocketing, and it is supported by "pocket" commands in most NC languages. In the present case, the operation might be justifiable because of its ability to repeat a weld sequence that minimizes distortion.

Knowledge gaps in structural fabrication requiring research seem to exist concerning distortion control and removal, predicting size change, distortion compensation strategies, and fast cutting methods that make two good edges.

2. <u>Pipe</u>

Automation of pipe fabrication is currently limited by the following:

a) difficulty predicting bend allowances for automatic bending.

b) pipe designed to be cut into too many little pieces for reassembly into rather small spools. This creates too many joints, often too close together, and too many made on board. For example, an FFG-7 has about 87000 feet of pipe, of which about 60000 are one inch or over in diameter. These receive 21000 cuts and are reassembled into 10000 spools. Thus the average spool is about 6 feet long.(4)

c) incomplete cost model of design-fabrication tradeoffs. Fbr example, sleeve joints require twice as many welds as butt joints, but they are easy welds and cause no drip-through problems that force designers to specify backing rings behind butt joints. Backing rings add weight and flow restrictions, and butt welds are harder to automate. A rational way out of this maze is needed. The yards we visited differ greatly in their approach to specifying pipe joint types. The relevant MIL STD is not a restriction.

d) lack of jigging methods that can deal with many diameters and combine holding with measuring. Straight pipe is the easiest to deal with, and the Japanese have thought up new assembly sequences to keep things straight as long as possible. Fully automatic pipe spool-making machines have been built as well.

The most automated pipe shop in U.S. shipyards is at Avondale. Automated or semi-automated activities include selecting pipe from storage, blasting and painting inside and out, cutting to length, beveling ends, welding on flanges, bending, forming branch extrusions, and welding fittings onto the extrusions. So far it has been used mostly to make fairly simple steel, flanged pipe pieces.

Knowledge gaps in pipe fabrication exist concerning how to divide a design into spools for efficient fabrication and how to cost-model alternate designs.

3. Vent

Like structure, vent fabrication is highly automated in cutting out the basic pieces but is mostly manual after that. Among the main limitations to further automation are:

a) too many odd-shaped pieces, all cut out into separate items that have to be held by someone while someone else welds them back together

b) too little use of crimp methods for joining. Commercial vent fabricators use this method even for doubly curved transition pieces. See Figure IV.6. Instead, two- or four-hand stick TIG welding is used, which is slow and expensive.

c) lack of jigging methods

d) designs that yield too many, too short (average about 24”), too odd-shaped pieces. Tightness of space makes such designs necessary, and CAD methods make it “easy” to create them. See Figure IV.7. Standard shapes are used (some yards think 29 shapes are needed, while others get by with 12), but standard automated bending and joining equipment geared to the standard shapes does not exist.

e) lack of use of standard available shapes and runs, and lack of curved versions of simple straight sections like Spiroduct.

No obvious knowledge gaps exist, but vent fabrication could benefit from use of simpler joining methods and alternate materials. NAVSEA’S ongoing study of vent fabrication alternatives and updating of specifications is discussed in Section IX. If functional alternates to vent functions were used, like local heat and cooling run by electricity, then fan rooms would be less crowded and *there* would be fewer and less contorted ducts. This would automatically simplify vent fabrication.

E. Economic and Cost Data

Economic and cost data, vital for rational choice of fabrication methods, seem to be in short supply. Data on cost distribution between labor and materials are quoted by the National Research Council in 1984 and Daniel Todd in 1985 (5.7). These and most *other* publicly available data refer to merchant ships, and it is obvious that they greatly understate outfitting costs in combat ships.

It appears that the yards must look closely at their operations in order to find out what it really costs them to build ships. For example, one pipe shop found that over 25% of a pipe fitter’s time per spool was spent searching for the correct material. Equipment has been purchased to eliminate this wasteful cost.

It is important to recognize how much work is required to determine current costs and methods. One yard spent $500,000 on a feasibility study to justify a $5,000,000 automation investment.

F. The Outlines of a Strategy

The above findings point to the conclusion that Flexible Automation is driven by requirements which in turn may or may not be known. If they are not known, then basic research is needed. Even if requirements are known, current designs may be infeasible for automation. To remedy this requires devising new techniques or materials, importing methods from other industries, and studying requirements again in order to redesign intelligently. Since requirements include tolerances, there needs to be attention to measurement methods. If feasible, functional, automatable designs can be devised and requirements written for task execution, then the specifications for automated equipment can be written, allowing development, economic analysis or purchase to occur. These steps comprise a rational strategy for implementing Flexible Automation. The strategy is illustrated in Table IV-1.

Table IV-2 shows qualitatively the relationships we have deduced between cost sources and phases of shipbuilding. From this table it would appear that the yards have the most to gain at first by attacking the high cost item that is under their control, namely management of the outfitting process. A formidable knowledge gap exists here, since there is no theory or methodology for outfit planning. Outfit sequencing and scheduling are done manually. Some yards leave tops of units open longer, while others tend to join units lengthwise sooner. one strategy favors outfitting while the other favors structure and protection from

TABLE IV-1 OVERALL FLEXIBLE AUTOMATION LOGIC

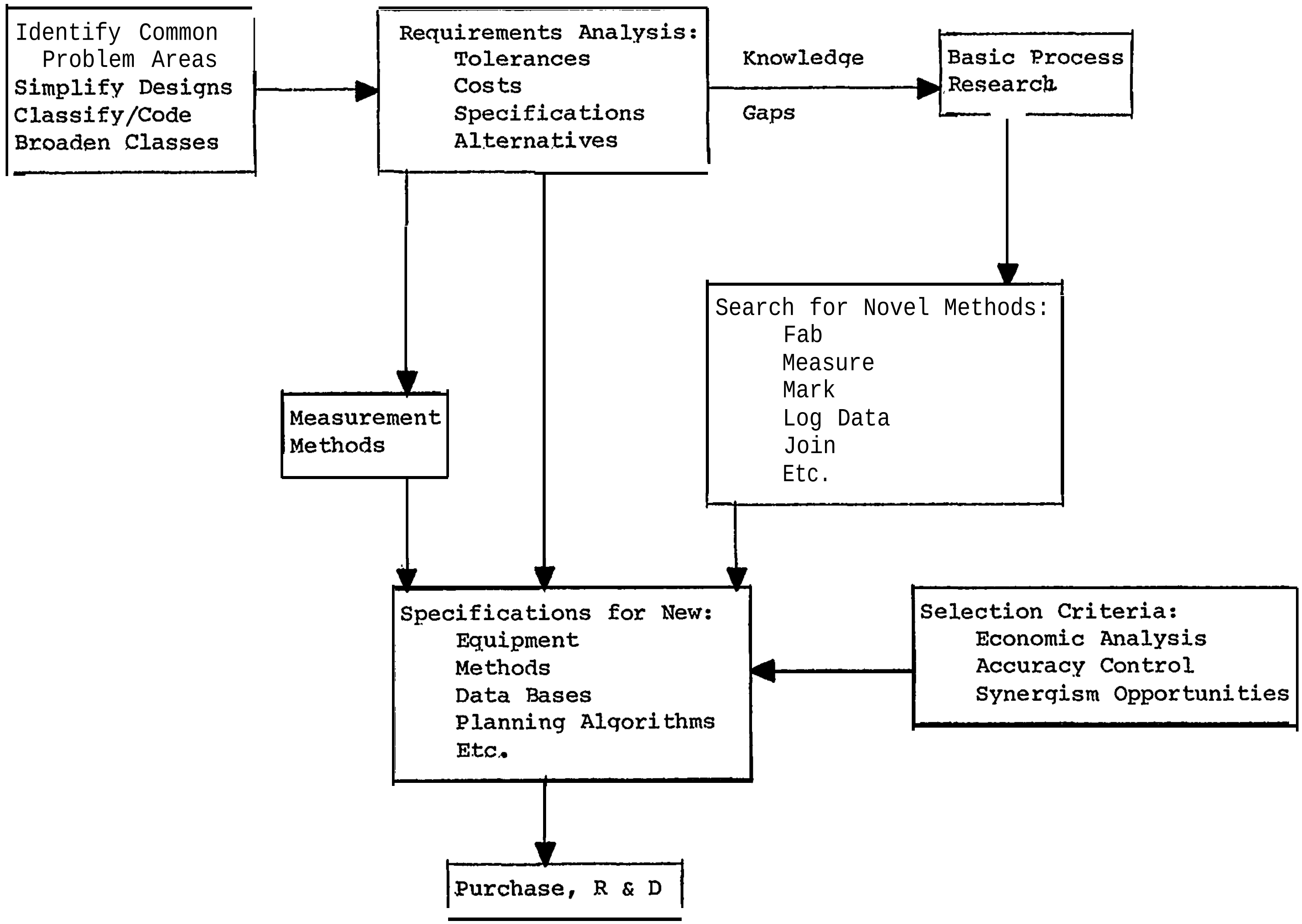


TABLE IV-2 Relationships Between Factors and Opportunities in Shipyard Productivity

	Fab of Components & Erection of Structure	Other Assembly and Outfitting	Trend or Opportunity
Cost Contribution	Smaller	Bigger	Fab Bigger Outfit Smaller
Automation Opportunities	Bigger	Smaller	Fab Still Bigger
Cost Influences	Design & Processes	Management & Planning	Management & Planning Impact Design and Process More Heavily
Responsibility for Cost Influence	Navsea, ABS, Design Agents	Shipyard	Yards Try to Gain More Influence in Fab

the weather. Outright automation opportunities seem to be rare in outfitting, but some may turn up in material handling or measurement. For example, we saw no elevators at yards we visited that are like those attached temporarily to buildings during construction. Likewise, we did not observe any yard using solid reference marks for measurement during outfitting. Such marks could be attached to modules during construction.

Deeper strategy issues and greater opportunities arise from attempting to design ships and their parts to be suitable for zone outfitting. An example is the pipe shop automation at Avondale. The strategy seems to be as follows:

1. Automate cutting, bending, and attaching flanges
2. Design pipe pieces to have only a few bends and branches
3. This requires more non-shop joints than other pipe design strategies
4. Instead of making these extra joints on board, which is difficult, make them on pre-outfit machinery units in another shop, which is easier
5. Load these machinery units, pre-tested, into the ship, and make the last few pipe joints there

This strategy works well on large ships where the machinery units can be both functionally and physically independent. Such units have been used on frigates in Great Britain but not yet on U.S. frigates.

The objective of this strategy, of coursef is not merely to automate the cutting and bending of pipe, but to systemize the fabrication, installation and testing of machinery systems.

AS progress is made in outfitting, the cost balance will swing toward fabrication, increasing the pressure to improve tolerances, reduce rework, and improve delivery times through automation. The yards will have to analyze their problems one at a time, including identifying knowledge gaps that deserve research funding. Such gaps clearly exist in outfit planning, design rationalization, design-manufacture interfaces, error propagation models, equipment location and pipe/vent routing, and novel joining methods for non-structural items, to name a few.

Solutions in most cases cannot follow the Japanese model of massive investment in huge machines, except in certain structural shops where there is no alternative given the required forces. Low production volume and smaller percentage of cost in fabrication will limit the opportunities unless low cost, mobile, and focussed solutions are found.

Some problems must be designed out. Others must be solved using small equipment. Hence the recent Japanese interest in 50 pound portable welding robots and crawling robots that do boxwelds.(6) pipe and ventshop automation also seem within reach, given better design and alternate methods for making duct.

G. Promising Trends

Two important events are occurring that offer promise for the future. The first is increased awareness of Japanese methods that emphasize planning, grouping of similar jobs, and the zone method of design and construction. The second is the emergence of new Ocean Engineering graduates with sensitivity to producibility problems.

Several U.S. shipyards have had close relationships with Japanese yards and have begun to adopt advanced methods. Of these, the most easily accepted and adopted seems to be preoutfitting in zone construction. on the agenda is accuracy control, but this is a much more complex activity that requires experience, data, repeated production of similar workpieces, and an improved science base. U.S. yards are just beginning to recognize its merits, and may not realize its complexity.

New graduates will be the carriers of this activity. Unfortunately, only one university's curriculum in Ocean Engineering deals with production control and production methods, and none deals with producibility in ship design. The emphasis in coursework and professional research is on classical design issues. This will have to change.

H. Summary

This section compared current shipbuilding practice to the requirements for flexible automation and identified several gaps. The implementation strategy outlined in subsection F assumes that

- currently available common automation equipment may not be suited to shipyard jobs
- design of automation equipment that is suitable depends on clear statements of job requirements, which depend in turn on understanding of the process
- effective use of automation depends on finding or creating enough jobs with enough similarity to make automation economically and technically feasible

To fulfill these assumptions and pursue the strategy outlined above, the yards, design agents, and the Navy need to strengthen product-oriented shipbuilding, rationalize designs, and acquire better understanding of processes, design requirements, and tolerances.

The next several sections go into detail on the issues discussed above: planning, design, economics, pipe, vent and structure.

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Small crawling welders (Nippon Kokan)

Crawling E-beam welder (France)

One side MIG welding with Cu backing (Nippon Kokan)

Outside hull crawling welders (NV Phillips)

Rationalization of Hull Design (Denmark)

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MIL STDS and ship specifications:

MIL STD 22D	Welded Joint Design
MIL STD 278E	Fabrication, Welding, and Inspection for Machinery, Piping, and Pressure Vessels
MIL STD 777D	Schedule of Piping, Valves, Eittings and Associated Piping Components
MIL STD 1627B	Bending of Pipe or Tube for Ship Piping Systerns
MIL STD 1689	Fabrication, Welding, and Inspection of Ship Structure
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Product Work Breakdown Structure

Integrated Hu1l Construction, Outfitting, and Painting

Design for Zone Outfitting

Jane’s Fighting Ships

V. MODERN SHIPBUILDING METHODS AND THEIR RELATION TO FLEXIBLE AUTOMATION

This Section describes modern shipbuilding methods as we have seen them being practiced in several U.S. shipyards. The planning problem is discussed first, followed by design. In each case we note the complexity and observe how automation could improve each activity.

How Planning is Done

Planning is a yard activity, and is done by the building yard. The purpose of planning is to arrange for efficient building of a ship or a group of ships. very generally, this is to say that planning properly assures that costly elements of shipbuilding, materials, labor, and capital, are by design utilized in productive, effective ways.

1. Potential Ranges of Planning

At the very least, planning deals with the yard and its shops, and addresses a given ship design to be built in an existing yard. Planning, however, may be usefully extended into the design process at the detail, preliminary, or even concept level, and into the realms of yard method, tools, technology, and layout. It is easy to imagine planning as an extensive yard activity reaching into ship design from the concept stage onward and into yard design as well, since there are many examples from history of such a reach of planning. Examples include Japanese tanker production in the 1970's and the yards involved, Ingalls' Pascagoula yard for building Spruance-class destroyers, the design of cargo ships (Liberty Ships) and tankers for the WWII era; River Rouge and the Eagle boat, Hog Island, and The New york Shipbuilding Corp. Conversely, early and recent examples of minimally-involved planning can be found.

The extension of the yard planniNg activity beyond the existing yard and shops properly remains controversial because serious issues follow extensions of planning. Issues include the conflicts between efficiency and versatility, versatility with respect to both new ship designs and new building methods; and the questions of design, performance, and margin compromises that occur during planning-design interactions. Indeed, such extensions of planning into ship design and into yard method have had mixed results, including some great failures and spectacular successes. Notwithstanding, the entire realm of planning is firstly a realm that has great leverage on yard productivity and, secondly, extensive potential applications for flexible automation, albeit not always or not only automation in the sense of manipulation of hardware.

Issues beyond the direct control of ships' designers or ships' planners often determine the range that planners will have for a shipbuilding program, whether the planners' influence will reach to the concept design level or to the level of shipyard capital decision-making. One determinant of the reach of effective planning may well be the matter of who does the concept, preliminary, contract, and detail design; possibilities range from the customer through customer design agents, yard design agents, or the yard’s own design group. Most combinations have occurred, usually depending on the level of control the customer wishes to maintain over the design. This is illustrated, to the extent of our understanding, in Table V.A.I. Another determinant of the reach of planning is the size and certainty of the building program; the program-specific yard modifications that a yard can accomplish depend on the size and length of the cash-flow stream a program generates as well as the yard’s perception of the likelihood of similar follow-on business.

2. The Characteristics of Planning

A major product of the planning process is the assembly and process sequence for a ship. A simplified example of two approaches by different yards is shown in the Figure VA.1. The

TABLE V A.1

EXAMPLES OF EXTENT OF YARD PARTICIPATION IN SHIP DESIGN

DESIGN STAGE ↓ / PROGRAM →	DDG 51 AEGIS DESTROYER	CG 47 AEGIS CRUISER	DD 963 DESTROYER	COMMERCIAL JAPANESE-BUILT TANKER CA. 1975-1980
CONCEPT DESIGN	CUSTOMER	CUSTOMER	CUSTOMER	YARD
PRELIMINARY DESIGN	CUSTOMER *	CUSTOMER	YARD +	YARD
CONTRACT DESIGN	CUSTOMER OF CUSTOMER'S AGENT.	CUSTOMER'S DESIGN AGENT	YARD +	YARD
DETAIL DESIGN	YARD'S DESIGN AGENT. *	YARD +	YARD AND YARD'S DESIGN AGENTS +	YARD +
BUILD	YARD. FOLLOW YARD. *	YARD. FOLLOW YARD. *	YARD *	YARD *

* PLANNING OCCURS OR OCCURRED (KNOWN).
\+ PLANNING ACTIVITY IS LIKELY TO HAVE OCCURED.

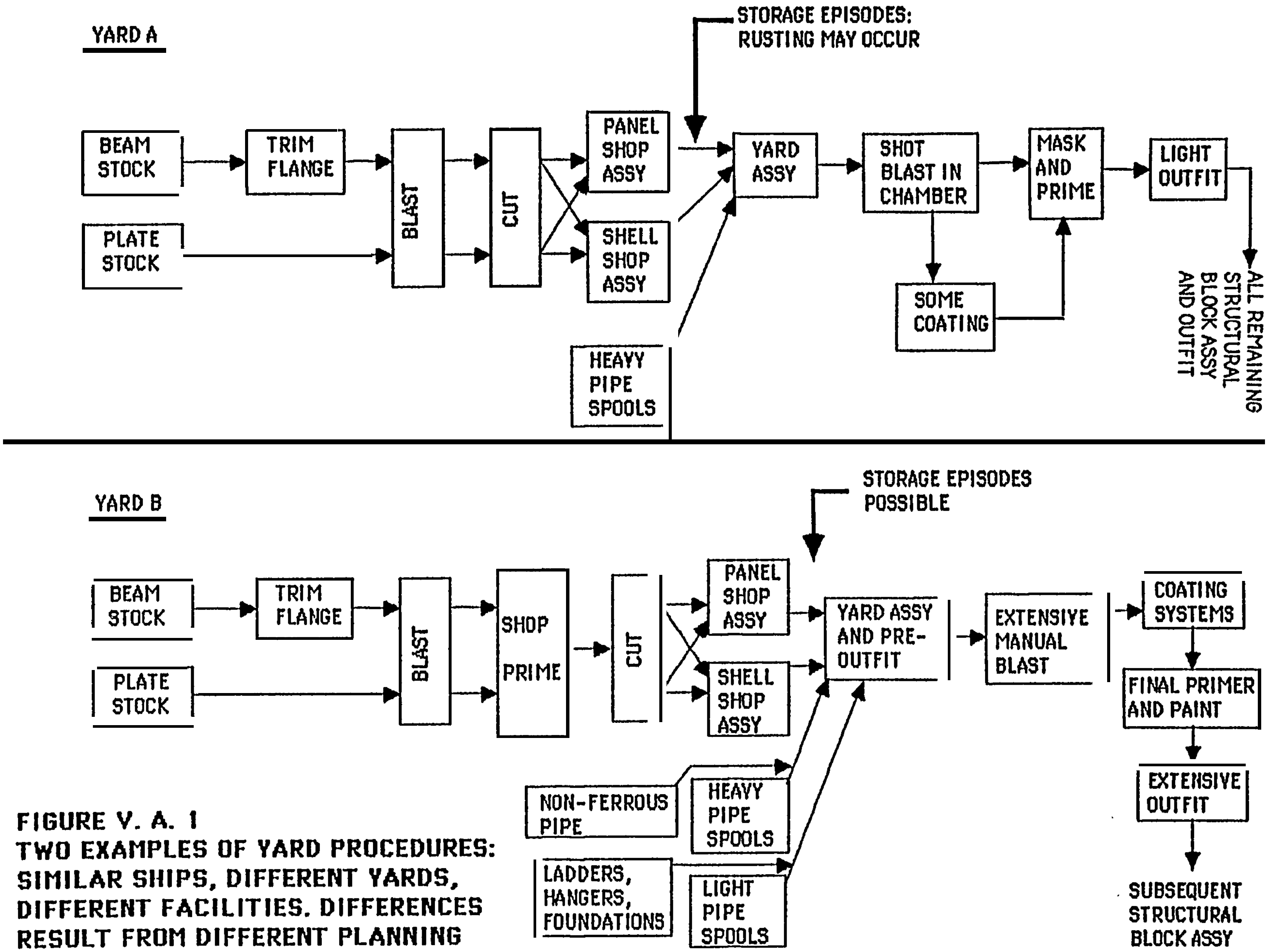


FIGURE V. A. 1
TWO EXAMPLES OF YARD PROCEDURES: SIMILAR SHIPS, DIFFERENT YARDS, DIFFERENT FACILITIES. DIFFERENCES RESULT FROM DIFFERENT PLANNING DECISIONS

planners' freedom for producing diverse sequences is constrained by various choices and decisions made at the yard or at design offices or customer’s specifications reviews. A limited view of such choices and decisions and their association with various design levels, is given in Table VA.2. Part of the planners’ job is to foresee consequences of design, planning and yard decisions, as well as interactions between pairs or sets of decisions. Interactions between decisions are not explicit here, but implicit. Thus, part of the artistry of planning can be characterized as creating efficient process and assembly sequence structures within the sometimes-negotiable constraints of ship's design, ship’s spec, and yard; this creation requires a running knowledge and foresight of the implications of planning, design, and spec decisions on both other such decisions and on candidate process and assembly sequence structures.

Shipbuilding typically involves long and complicated sequences of assembly, measuring, welding, cleaning, coating, and forming steps. Neither the sequences nor the processes are wholly constrained by either design or ship's spec, though there are significant constraints. That is to say, planners have freedom; they have more freedom if influence over design or ship’s spec is a possibility.

Since sequences are long and complicated, planners' decisions can have long reach; that is, consequences of a decision may appear quite far away in the process stream from the event directly affected by the decision.

That this is so is illustrated in Fig. v.A. l-a which depicts portions of process sequences for a particular ship and spec being built at two different yards. The figure contains an example of a process decision influencing subsequent steps, namely, the decision by Yard B to put shop primer on raw stock after blasting. Subsequent rust-removal blasting is not needed but local cleaning prior to subsequent welding is required in the case of certain high-yied steel materials. An example of a process decision influencing prior process steps is the decision by Yard A

TABLE VA. 2.
Planning Activity Associated with Design Levels

Planning at Concept, Preliminary & Contract Design Level

Interactions occur between design changes & design decisions specifications on *one* hand, yard physical, procedural, and skill-level characteristics on another, with implied build sequences, work quantities, skills, trades, & labor mix. Block & zone breakdowns are made, as are decisions implying possibilities of unit construction, block outfitting and outfitting stages. Planning work has great leverage but is very difficult at this level. The yard consequences of decisions made at this stage are difficult to comprehend, not fully explored, and sometimes unanticipated.

Planning at Detail Design Level

Planning decisions based on choices which remain as yard options can be made and may include details of grand-block and block geometry and order and method of structural assembly, sequences of build and process. Available planning decisions may include those regarding stages of pre-outfitting, building on-block, building on-unit, erection on ship, and order of assembly, with implications for where the work may/must be done (i.e., indoors, outdoors, roomy, cramped; in-shop, on-ship) and for logistics of men and tools. System priorities and installation orders of pipe, vent, cable, and systems are decided. Sequence of design itself is determined, as is sequence of material acquisition. Freedom for some or much of the planning at this level may have been pre-empted by earlier decisions. Yard consequences are generally comprehensive, but not always well-explored, and can be unanticipated.

Planning at the Yard Level

A sequence of process and assembly steps consistent with the design and all specifications can be created for each generic element: Block, Unit, &c. A build sequence can be determined. A schedule can be determined. Work packages, material and equipment order schedules, and shop, labor, and craft requirements can be determined. The environment (i.e., pre-outfit stage, on-block, on-unit, on-board) for assembly and installation of the packages can be determined. Yard transport requirements for men, tools, and material may be implied and can be determined. Freedom for some of the planning at this level may have been pre-empted by earlier decisions and planning. Most effects of most decisions at this stage are readily visualized.

Planning at the Shop Level

Schedule trades, labor, and equipment against the work packages and schedules. Respond to internal or external contingencies.

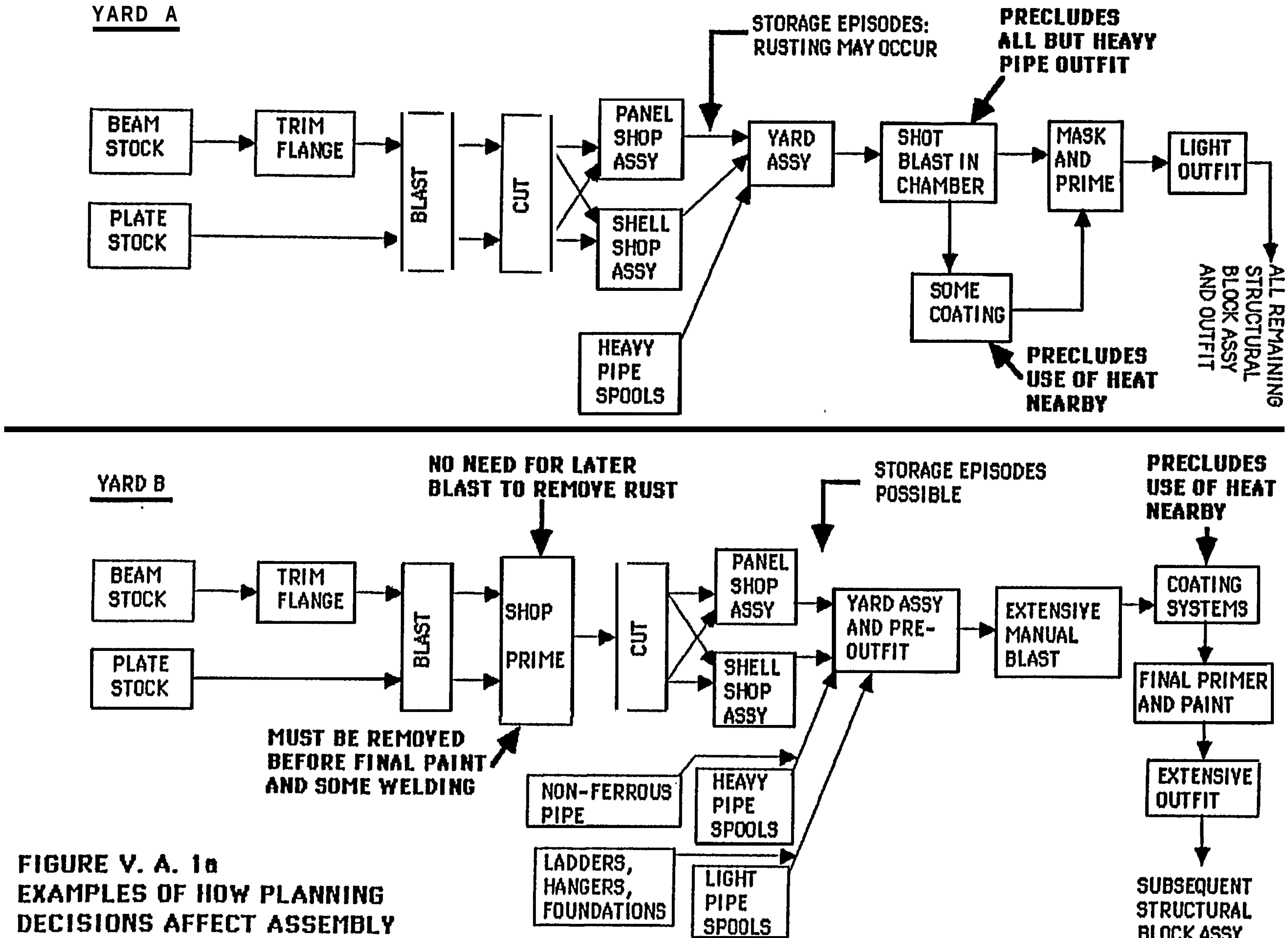


FIGURE V. A. 1a
EXAMPLES OF HOW PLANNING DECISIONS AFFECT ASSEMBLY SEQUENCES AND PROCESSES

to use an unmanned shot-blast chamber after block assembly, precluding all but the heaviest pipe from prior pre-outfit. Some consequences of these decisions, as observed by us, are summarized in Table VA. 3.

The examples, the textual table V.A.2, and the figures V.A.I and v.A.la, try to convey the nature of planning as an extensive yard function, with consequential reach potentially far from as well as near the area in question, complex, and a critical determinant of material, labor, and capital costs. two of these characteristics, planning bears some similarity to chess-playing; namely, both are complex, and both involve reach, after a decision or a move, which is potentially quite remote from the move or decision itself.

Planning thus is the province of very experienced persons with well-developed abilities to mentally generate and scan sequence trees to determine the effects of particular changes. Such a person would be dealing with past knowledge (e.g. "we had a sequence like that in place in the past and it had to be modified at A, to B, to accommodate spec. change C") or generating new knowledge ad hoc ("We've never installed E at this stage of assembly; to do so requires F & G prior but relieves J & K way down at stage L").

3. Possibilities for Automation of Planning

Planning the construction of a ship, however, is not necessarily done by an individual but usually by a changing team, so that opportunities for "practice" are fewer, and are certainly much less structured. It occurs to us that there are opportunities for automation of some aspects of the planning function. What is envisioned here are software aids to assist practitioners of planning in keeping track of constraints to planning and in exploring the consequences and interactions of constraints and decisions of planning choices.

In this regard, the aids envisioned are similar in a sense to the software aids to structural design that are already accepted and well-understood. In structural design, ships' structural

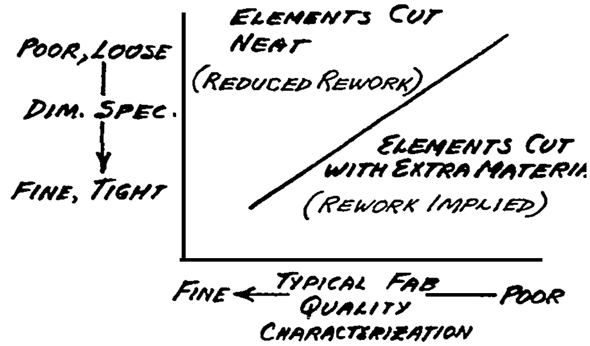
TABLE VA3

EXAMPLES OF EFFECTS OF DESIGN DECISIONS AND YARD DECISIONS ON SUBSEQUENT FABRICATION CHOICES

(EARLIER IMPOSITION OF CONSTRAINTS ON PLANNING)

DECISION ENTRY	CONSEQUENCES OF ENTRY	SOURCES OF ENTRY
HULL MATERIAL CHOICES		CONCEPT OR PRELIMINARY DESIGN - WEIGHT-ASSIGNMENT, LOAD, SCANTLING DECISIONS.
1020	ALLOWS GRAVITY WELDING. WELD-THROUGH PRIMERS AVAILABLE.	
HY80	WELDING PRE-HEATING REQUIRED. NO LOW-TECHNOLOGY AUTOMATED WELDING. NO WELD-THROUGH PRIMERS. {REMOVE PRIME BEFORE WELD OR DO NOT PRIME BEFORE WELD.	
HSLA	NO LOW-TECHNOLOGY AUTOMATED WELDING. WELD-THROUGH PRIMERS PERMITTED.	
SHOP PRIMER USED		YARD OPTION YARD DECISION
NO	HEAVY BLAST NEEDED BEFORE WELDING OR OUTFIT.	
YES — CONVENTIONA	REMOVAL REQUIRED PRIOR TO FINAL COATING SYSTE LOCAL REMOVAL REQUIRED PRIOR TO WELDING (HY80).	
YES — ZINC-BASE	REMOVAL REQUIRED PRIOR TO FINAL COATING OR LOCALLY PRIOR TO WELDING.	
COATING SYSTEM USED		SHIP'S OR CUSTOMER'S SPECIFICATION
MODERN RUST-PROOFING COATINGS	NO CONSEQUENT WELDING IN COATED AREA. HEAT-SENSITIVE AND REPAIR-RESISTANT. REMOVAL OF RUST AND SHOP PRIMERS REQUIRE.	
CONVENTIONAL COATING TECHNIQU	REPAIRABLE. RUST-REMOVAL REQUIRED	
YARD BLAST TECHNIQUE ON STRUCTURE		YARD OPTION YARD DECISION
OVERALL BLAST IN CLOSED INTENS BLAST CHAMBER	EXCEPT FOR VERY HEAVY PIPE OR SIMILAR, PRIOR OUTFITTING IS PRECLUDED.	
SELECTIVE MANUAL BLAST	LITTLE OR NO OUTFIT RESTRICTION. DEMANDS PRE-BLAST OF RAW STOCK AND SUGGESTS NEED FOR SHOP PRIMER USE.	
PROGRESS PAYMENT ALGORITHM	THE PROGRESS PAYMENT ALGORITHM (IF ANY) CAN INFLUENCE YARD DECISIONS REGARDING ORDERING OF MATERIALS, OUTFITTING OR ASSEMBLY SEQUENCE, FABRICATION SCHEDULE, YARD STORAGE NEEDS, &c.	CUSTOMER PROCUREMENT POLICY

TABLE VA3 (CONTINUED)

DECISION ENTRY	CONSEQUENCES OF ENTRY	SOURCES OF ENTRY
FAIRNESS SPECIFICATION δ CHARACTERIZES YARD PRODUCT, δ_0 IS SPECIFICATION	$\delta = \delta$(MATERIAL, MAT'L THICKNESS, YARD, &c.) $\delta_0 > \delta$ NO REWORK OR RESHAPING PROCESSES IN GENERAL USE OR NEEDED — LINE OR SPOT HEATING, JACKING — AFTER FAB. $\delta_0 < \delta$ REWORK OR RESHAPING AFTER FAB GENERALLY NEEDED.	SHIP'S OR CUSTOMER'S SPECIFICATION AND YARD POLICY, YARD DECISION.
DIMENSIONAL SPECIFICATION		
YARD QUALITY ASSURANCE, ACCURACY CONTROL POLICIES	WORK QUALITY AND CONSISTENCY. TOOL QUALITY, MAINTAINENCE, CONDITION. PREDICTIVE KNOWLEDGE OF YARD PRODUCT OR LACK OF KNOWLEDGE. CONTROL, PREDICTION, AND KNOWLEDGE OF REWORK.	
SHIP'S LINES & GEOMETRY CURVED OR STRAIGHT: STEM, SHEERS, TRANSOM, WEATHER DECK	AFFECTS YARD ERECTION TECHNIQUES, MEASUREMENT & VERIFICATION TECHNIQUES, QUANTITY OF WORK, LAYOUT TECHNIQUE. AFFECTS THE NEED FOR LINE OR SPOT HEATING OF PLATE ELEMENTS AND PLATE FABRICATIONS.	DESIGN STAGES - CONCEPT, PRELIMINARY, OR CONTRACT DESIGN.

design included, design synthesis, the "creative" Part of structural design, remains largely in human hands. Typically a designer re-arranges scantlings, frame spacings, and essential geometry of a structural design; software aids are involved in calculation and comparison of stresses, stiffnesses, weights, moments, and centers.

Various computer software can be developed or already exists that can support and aid the planning exercise at anY level. A data base and data-base management system can be used to store and keep track of specifications, design, and planning decision entries associated with (foreseen) consequences of entries, source of each entry, and (foreseen) interactions between entries. Retrieval can be by logical combinations of system, part, process, source, consequence, affected elements, &c. Assembly and process sequence graphics can be generated, stored, and varied with computer graphics software, and one can envision the capability of flagging assembly and process sequence elements that are subject to the (foreseen) consequences of a changed specification or a changed process step. Process simulation software and various costing and manning subroutines can be invoked for comparisons between assembly and process sequences.

The promise is to augment the skills of the experienced planner by various means. More assembly and process sequences can be explored, and extensive experience, to the extent that it can be characterized, is available readily and by association. The ability to explore sequences for consequences of change, or "foresight," to the extent that it can be codified, is readily invoked. Representations of candidate process sequences are easily transported, stored, recalled, operated on, and available to all appropriate parties.

4. Summary

Planning is a yard activity with the purpose of arranging for efficient utilization of the costly elements of shipbuilding - materials, labor, and capital. The foregoing discussion has addressed one aspect of planning and an associated opportunity for automation, that of generating and exploring the plan and its physical manifestations. For planning to be most effective, there must be a goal that is more precisely stated than “arranging for efficient utilization of the costly elements of shipbuilding,” and there must be means of measuring various plans against the goal. For various reasons, these aspects of planning may be beyond attainment, though if there were any hope of economical attainment, said hope would involve extensive computational “automation”.

The matter of the planning goal might be considered first. One can easily create a list of tens of different planning criteria or “goals,” many local, some global, and by no means all consistent (e.g. Table VA.4). Any entry in such a list of planning criteria may well be appropriate for certain situations, and a few entries may be appropriate for many situations. Most entries, however, are local. Attempts to generate useful global criteria are met with various difficulties, one of which has got to be the question of the time window and weighting function, or filter, to associate with the candidate criteria. Under some circumstances and not rarely, global criteria and their associated time window may come in conflict with yard policy in terms of investment, development, or technology-change goals. Additionally, our own past experience in trying to enforce a global criterion in a simpler example system with many technology choices showed that small changes in production goals generally led to staggering across-the board changes in technology! Means to suppress such an unwanted result of blind application of a criterion may include embracing a strong component of capital expense limitation in any global planning criterion, or to stick to multiple local planning exercises guided by combinations of non-interfering local planning criteria. That planning criteria can be inconsistent or contradictory can be seen easily in many examples; one such is to consider cost minimization in a pipe-shop where one may have to choose amongst criteria which may include minimization of cost/length, per weight, per spool, &c. Clearly if the weight of length per spool changed from time to time or

TABLE VA. 4

EXAMPLES OF PLANNING CRITERIA

LEVEL-LOADING OF A SHOP
A TRADE
A YARD BOTTLENECK.

MINIMIZE MAN-HOURS
YARD-HOURS
LABOR COSTS
CAPITAL EXPENDITURES
NUMBER OF STRUCTURAL ELEMENTS CUT WITH EXTRA MATERIAL
PROGRAM COST
MATERIAL HAULAGE (Σ |Weight x Distance|).
MAN HOURS ASSOCIATED WITH TOOL, PART, OR SELF-TRANSPORTATION

MAXIMIZE PRODUCTIVE THROUGHPUT IN YARD
IN SHOP (STRUCTURE) - WEIGHT/TIME
WELD LENGTH/TIME
PIECES/TIME

(PIPE) - WEIGHT/TIME
LENGTH/TIME
- SPOOLS/TIME

ARRANGE LOAD FOR EARLIEST RECEIPT OF PROGRESS PAYMENTS.
FOR LATEST PAYMENT OF MATERIAL COSTS.
OF LABOR COSTS.

ANY LOGICAL COMBINATION OF TWO OR MORE CRITERIA.

DESIGN TO MINIMIZE FRAME-TO-LONGITUDINAL CROSSINGS.

PLAN FOR EARLIEST COMPLETION OF AN ASSEMBLY.
A SHIP.

MINIMIZE SHOP COST (PIPE) COST/LENGTH
COST/WEIGHT
COST/SPOOL

from ship to ship, the two associated criteria cannot be simultaneously applied.

There are, of course, extensively automated or partly-automated accounting structures associated with accounting for the various costs that go into ship production. such structures address costs after being incurred, but similar structures they have that respond to planners' inputs and account for estimated costs are no problem at all. The problem, however, is an immense one, the problem of estimating the costs associated with the assembly-step and process blocks of several candidate sequences.

VI. COST INFORMATION, TIME-SEQUENCE INFORMATION, AND THE EVENTS IN A SHIP'S HISTORY.

A. Introduction

This section is a brief discussion of shipbuilding economics in terms of costs and times. Data are compared and displayed in Various ways and conclusions are drawn from the information on the cost-and time-scales of shipbuilding. These data represent another aspect of the environment of shipbuilding, an aspect which was more opaque and somewhat harder to learn about than the physical and design aspects of shipbuilding. Information has been drawn from many sources and combined with some impunity; additionally some of the information is word-of-mouth and some is representation of estimates of persons knowledgeable in their field. Where it has been possible, information is from credible published sources. Thus it is possible that there are inaccuracies in what follows, and there may be programs that are in ways exceptional to the following representations. In particular, the data are typical mainly of military non-nuclear, surface ships, with some comparisons to commercial ships where appropriate. Notwithstanding, we use and consider the following on the basis that partial and approximate information is still quite useful.

It is no surprise that there is a debate associated with ships' life-cycle costs. Ships are expensive and it is quite attractive to accede to a compromise when a ship is built which slightly lowers the acquisition cost at the expense of performance, or of fuel usage, or of ease of subsequent maintenance. Whether or not such compromises are successful depends on the use, or fuel cost, or life and environment that the ship faces in the future. Typically the rational customer considers projections of these factors from the present. The rational customer, however, cannot know that he must consider very carefully compromises involving acquisition cost against ease of maintenance unless he knows that maintenance and modifications costs over a ship's life can be much greater than the acquisition cost! Since our own comments, opinions, and advocacies occasionally involve design modifications or design compromises, we felt it was important to have some understanding of the entire cost structure across a ship’s existence. In a later chapter we use knowledge of a ship’s weight distribution and budget to screen ideas which involve structural design and weight changes in a way similar to the use of cost knowledge here.

There is also knowledge that is useful for making strategic and design judgments, inherent in the time-scales of ship design and building and the associated bid and contractual milestones and their timing. Some of this information is considered and presented here.

The reader will immediately notice that the information presented here and in much of this report is heavily biased toward non-nuclear surface combatants with little attention to commercial ships such as container ships, tankers, or work boats. This is a reflection of the situation both in terms of what was being designed and built in the design offices and yards available to us, and the information available to us from literature, texts, technical papers, and expert practitioners. The situation is a consequence of the costs of both raw materials and labor available to ship builders in this country as compared to that available in the Orient; and also a consequence of the experience of the 1970’s during which time the world tanker fleet experienced an expansion that allowed and drove many yards to enhance productivity. It is noted that productivity enhancement at a yard not only puts a yard in a more competitive position in terms of cost per delivered ship; it also allows a yard to compete for a larger market share of a boom market without expansion of its physical plant. Generally American yards did not have the strong incentive or consequently the opportunity to participate in enhancement of productivity to the extent found elsewhere, and the principal remaining customer is the Navy.

B. Cost Scales of Ship-Building

An example breakdown of Ships’ Life Cycle Costs is given, by fraction of category in Fig. VI.B.1, and by amount, in dollars, in

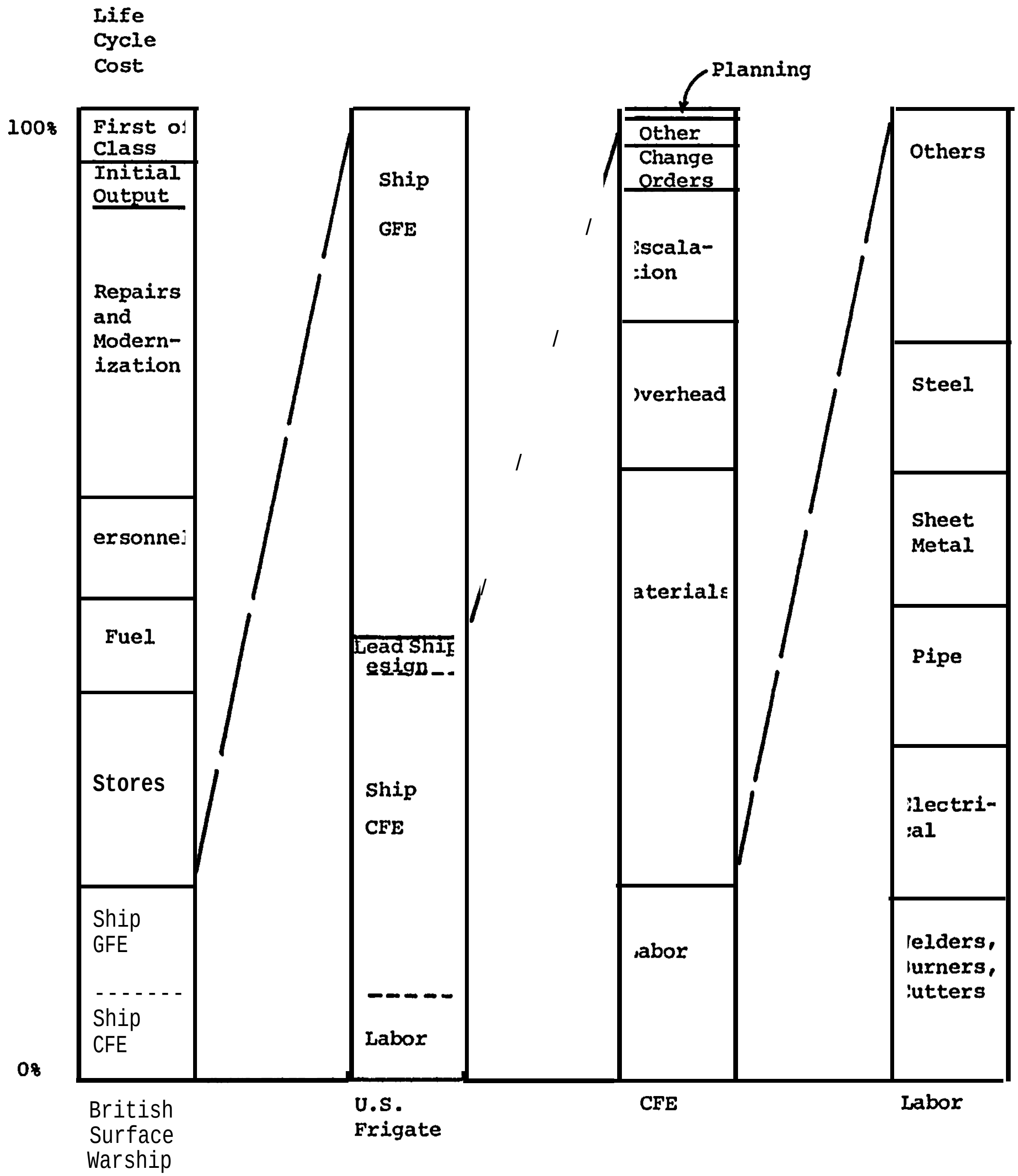


Figure VI.B.1. Ship Cost Breakdowns

TABLE VI.B.I

REPRESENTATIVE COSTS FROM THE LIFE CYCLE OF A SURFACE COMBATANT

LIFE CYCLE COSTS	FRIGATE COSTS	GFE FRIGATE	CFE & LABOR FRIGATE	LABOR FRIGATE
TOTAL *\$2000* 10^6	TOTAL *\$400* 10^6	TOTAL *\$220* 10^6	TOTAL *\$164* 10	TOTAL *\$33 10*
Maintenance & Mods 600 10^6	G.F.E. 220 10^6	Ordnance 132 10^6	Material 71 10^6	Welding, Cutting 6 10^6
Ship 400 10^6	C.F.E. 164 10^6	Electronics 59 10^6	Labor 33 10^6	Electrical 5 10^6
Stores 400 10^6	Profit 16 10^6	Project Growth 20 10^6	Overhead *25* 10^6	Pipe Shop *5* 10^6
Personnel 200 10^6		Hull, M&E. 9 10^6	Escalation 23 10^6	Sheet Metal 5 10^6
Fuel 200 10^6			Change Orders 7 10^6	Steel 4 10^6
1st of Class 1oo 10^6			Other 3 10^6	Other 8 10^6
Initial output 100 10^6			Planning 2 10^6	

Note: All entries are in dollars.
Source: Prof. Clark Graham, MIT, plus industry sources.

Table VI. B.1. The reader should note that each bar of the pargraph of Fig. VI.B.1. represents the fractional breakdown of a sub-category of a bar to its left; for example, the bar dividing shipbuilding labor by shop on the extreme right of the figure represents a break-down of approximately one-fifth of the "contractor-furnished equipment Frigate" segment marked "Labor." Thus, the magnitude of costs falls rapidly as one scans from left to right, as verified by the accompanying Table VI.B.1. Note that information of this form becomes an important design tool when one considers, say, a compromise that gives a 5% increase in structural welding productivity at a cost of a 2% increase in subsequent maintenance costs. Thus a savings of say, $150,000 at the building of a ship may end up costing about $3,000,000 over the life of the ship. The increase in welding productivity may be a proper choice during the midst of a war when the particular ship may have an expected life of the order of 20 months, but the wrong choice if the ship has an expected life of 20 or more years.

The reader may quibble over the entries in Figure VI.B.1, especially since they represent data from different sources, countries, and times. Notwithstanding, there is the fact that for use of such information as a design tool, the entries in the life cycle cost columns represent the compilers' judgement of cost effects many years or decades into the future, said judgments usually based on past experience. Over time, costs of commodities and labor have been sufficiently volatile or non-stationary to give rise to extensive betting games involving costs in future times. Thus, even with solid historical figures, the compilation of information such as represented here contains a large measure of uncertainty and bases for controversy. Imagine the position of the concept design team for the Spruance-class destroyers, in the late 1960's, having to predict the life-cycle cost of, say, fuel, for a ship class that will be commissioned subsequent to the mid-seventies.

Such limitations notwithstanding, the lesson of Figure VI.B.1. is that for a ship which may have a 20-to 30-year life, it may not make economic sense to accept design changes which save a fraction of labor or even material costs, at the cost of subsequent outlays for manning or personnel or for fuel, or most strikingly, for ships' maintainance and updating.

We do recognize that there are circumstances that emphasize the importance of acquisition costs and supress the role of operating costs. Yet, it remains for concept designers to evaluate such circumstances as well as to predict operating costs and to use the consequential information to drive the design and to guide trade-off decisions.

While the general form of the bars in Figure VI.B.1 may not change, various circumstances, some within the grasp of the designers or customer but some without, can greatly change magnitudes of the various entries. Examples include the following:

1. The purpose and sophistication of the ship affect the relative magnitude of shop charges as well as their absolute magnitude in the "Labor" bar; also, the magnitudes of labor and material in the contractor-furnished equipment (c.F.E.) bar.

2. For combatants, the nature of weapons system affects the magnitudes and balance of the ship-cost and government-furnished equipment (G.F.E.) bars. very sophisticated systems (e.g. Aegis) typically increase importance of G.F.E.

3. Personnel costs within the life-cycle cost bar for combatant ships are affected greatly by any change in national policy, as for example, from universal service with conscription to recruiting of a volunteer service.

4. A change in fuel feedstock costs from dollars a barrel to tens of dollars a barrel, or vice-versa, has a great effect on the importance of ships' fuel cost within the life-cycle cost bar.

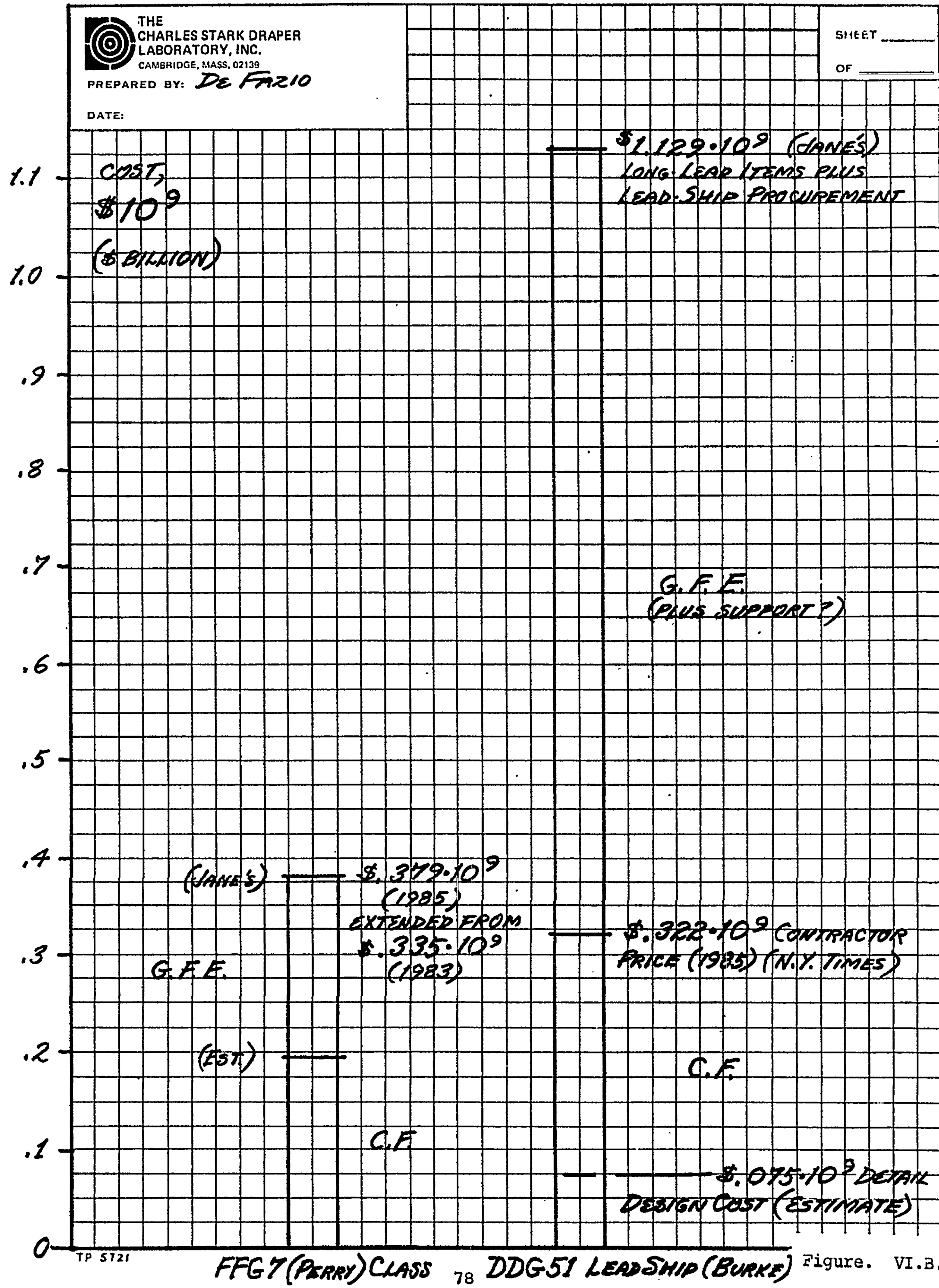
It is changes such as the last two which are essentially out of control of designer, builder, or customer; have effect throughout the life of the ship; and also have great influence on the relative importance of acquisition cost.

Item two just above is illustrated in Figure VI.B.2 where some published data, extended to account for inflation, and some word-of-mouth information has been combined to compare acquisition costs for two current surface combatants. The ships are examples of the Perry (FFG7) Frigate-class, and the Burke (DDG51) Aegis Destroyer-class. The Perry-class Frigate is the simpler craft of the two, a conventional guided-missile frigate, displacing under 3600 tons. The Burke-class Destroyer represents the lead-ship of a class that will carry the second-generation of the sophisticated Aegis air defense system and both ship-borne and towed-array sonar. The sophistication as well as the size of the Aegis ship is reflected in the cost and the cost fraction of the shipyard work. The Burke's comparable displacement will be about 8400 tons.

An immediate conclusion is that, with GFE so much larger in cost compared to CFE, some attention should be paid to the efficiency of vendors of such equipment.

One more comparison is worth making. Table VI.B.2, formatted as a pie chart in Figure VI.B.3, lists our best estimates for the costs of various phases of DDG-51 design and construction, expressed as totals or as cost per ship if 30 are built. At the right in the Table are the fractions of single ship cost. Thus the estimated $32 million spent on preliminary, concept, and contract design represent about 0.1% of the cost of each of 30 ships since each ship's share is just over $1 million and the total cost for a ship is nearly $1 billion. Thus the costs of design, and planning at the yard, are vanishingly small fractions of the total acquisition cost, not to mention life cycle cost.

It should also be noted that detail design and planning are done in a hurry on the basis of a low bid. There may be a great tendency to solve the formidable technical design and planning problems by accepting the first solution that meets specifications. There may not be time for optimization or improvement. We were told this explicitly more than once.


THE CHARLES STARK DRAPER LABORATORY, INC.
CAMBRIDGE, MASS. 02139
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(1983)
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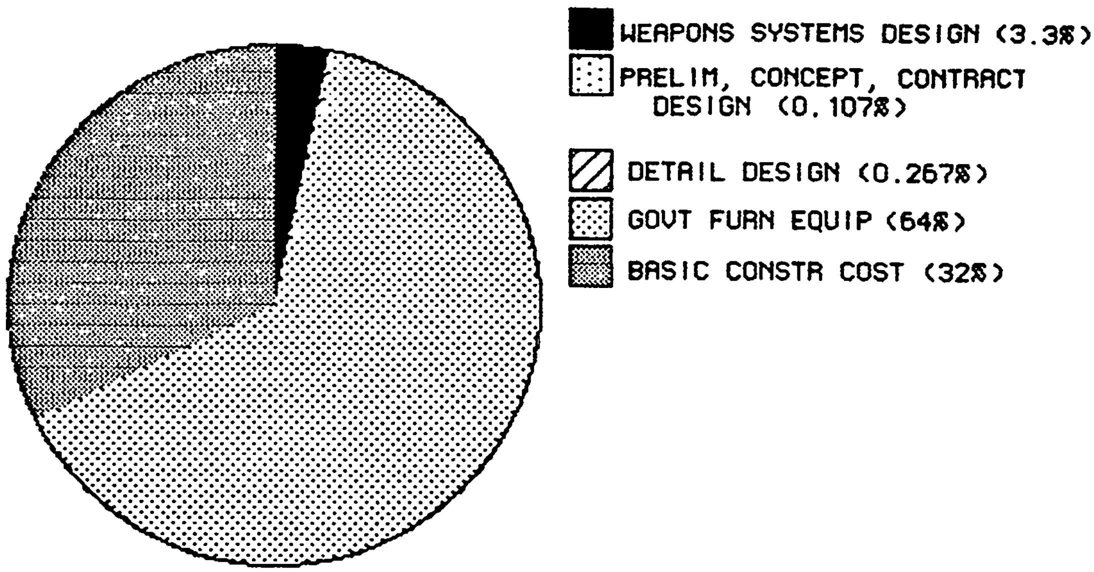
(EST)
C.F.
C.F
$.075·10^9 DETAIL
DESIGN COST (ESTIMATE)
TP 5721
FFG 7 (PERRY) CLASS
DDG 51 LEAD SHIP (BURKE)

Figure. VI.B.2

TABLE VI.B.2

AEGIS SURFACE COMBATANT

COST CATEGORY	**CLASS TOTAL**	PER UNIT	FRACTION OF UNIT
Concurrent (Weapons System Design)	\$ 1000 10^{6}	*\$33.3* 10^{6}	*.033*
Prelim, Concept, Contract Design	\$ 32 10^{6}	*\$ 1.07* 10^{6}	*.00107*
Detail Design	\$ 80 10^{6}	*\$ 2.67* 10^{6}	l *00267*
GFE	\$19,200 10^{6}	*\$ 640* 10^{6}	l *642*
Yard Cost to Buyer	\$ 9,600 10^{6}	*\$ 320* 10^{6}	*,321*
TOTAL	\$29,912 10^{6}	*\$997* 10^{6}	*1.00*



ECONOMICS OF SHIP DESIGN AND PLANNING COMPARED TO SHIP COST, AMORTIZED OVER A CLASS OF 30 DESTROYERS

Figure. VI.B.3

One can conclude from this that where knowledge is available, especially in detail design and yard planning, additional funds and time could be well spent to save production costs or time on many subsequent ships.

C. Time Scales of ship Building

In this section we review what we have gleaned, mostly from public data, on the time it takes to design, plan, and build ships. All of the data pertain to surface, mostly naval combat, ships.

The life cycle of a class of ships can be very long indeed. Design of the class can take 7 or 8 years, lead ship construction 3 years, lead ship life 20 years, and time from first to last ship launching 10 or more years. The last ship in the DDG-51 class may retire from service in 2018. Considering the rate of technological advance, it is easy to see why “Maintenance and Mods” in Figure VI.B.1 is so large.

Figure VI.C.1, from Bosworth, shows that typically many years are required to create a lead ship, starting with the earliest designs. Much of this time is devoted to debating extended issues such as mission and technological risk. Once a preliminary design is finished, the problems are almost purely technical, and solutions are required very rapidly.

When we look more closely at the construction phase we can see some similarities and differences between yards, time periods, and ship types. Typical data shown below are from Jane’s Fighting Ships. We compare time spans between keel laying, launching, and commissioning for U.S. Frigates in the 1960’s and 1970’s, Destroyer Tenders and Oilers in the 60’s, 70's and 80's, and Japanese Frigates in the late 1970’s and 80's. See Figures VI.C. 2 & 3.

Several conclusions are possible. First, some yards appear to have a learning curve and can deliver subsequent ships sooner than their first of class, whereas other yards do not show definite learning. Second, Japanese Frigates take 30 to 36 months to build. Some learning is discernable.

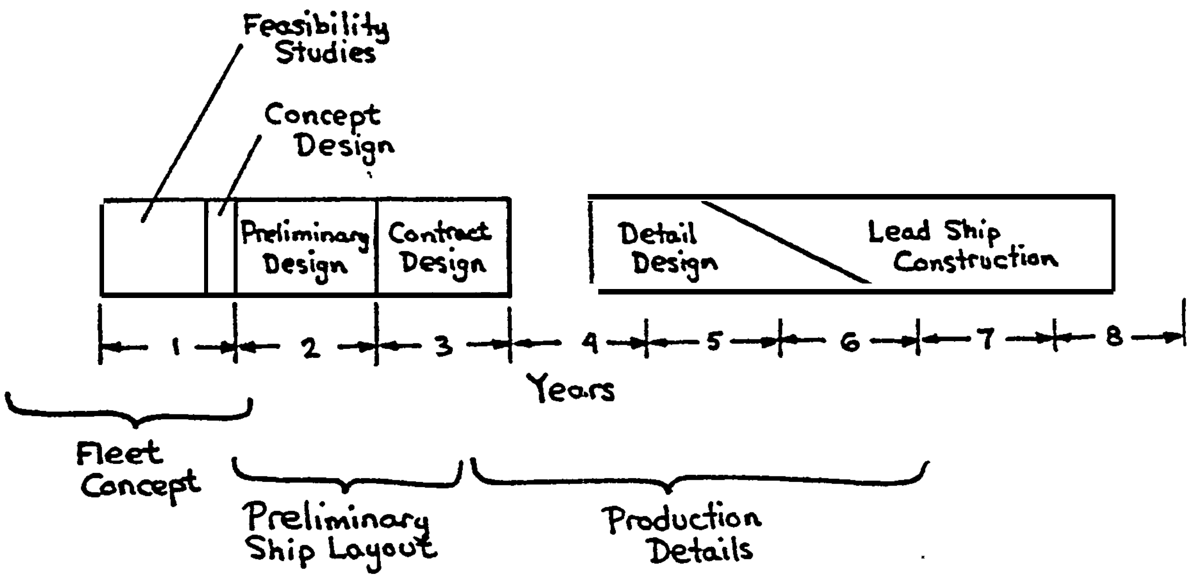


Figure VI. C.1. Time Frame for Producibility Categories

Hull	Date	Yard
AD 37	7/64	Puget Sound NSY
38	2/65	Puget Sound NSY
41	6/77	NASSCO
42	2/78	NASSCO
43	1/79	NASSCO
44	8/80	NASSCO

0 1 2 3 YEARS

x = Launch

+ = Commission

Hull	Date	Yard
AO 177	5/78	Avondale
178	8/78	Avondale
179	7/79	Avondale
180	8/80	Avondale
186	2/81	Avondale

Hull	Date	Yard
FF 1040	10/62	Bethlehem Steel, San Francisco
1043	4/63	Avondale
44	8/63	Avondale
45	9/63	Avondale
47	11/63	De Foe
49	2/64	De Foe
51	2/64	De Foe

Hull	Date	Yard
FF 1052	10/65	Todd Seattle
55	6/66	Todd LA
56	3/67	Avondale
58	9/66	Todd LA
59	4/67	Avondale
60	3/67	Todd LA
61	10/67	Avondale
77	1/69	These 20 in a row at Avondale
87	12/70	
97	8/72	

Figure VI.C.2. Combat and Non-Combat Shipbuilding Data on U.S. Ships

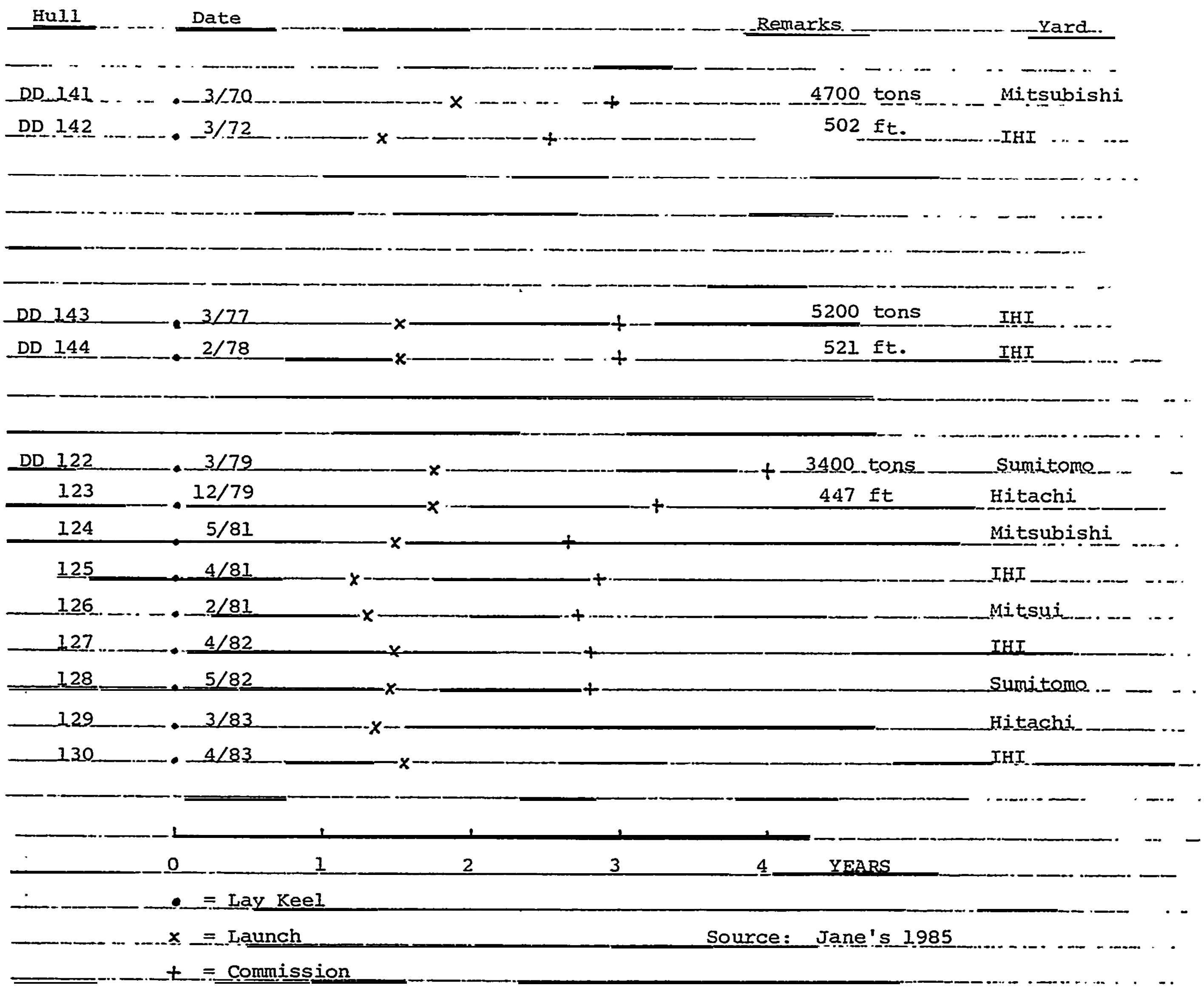


Figure VI.C.3. Combat Shipbuilding Data on Japanese Frigates

Extensive data on ship production schedules has been gathered and appears in Figures VI.C. 4-8. While the causes for variations between and within yards cannot be seen from these Figures, it is clear that some yards can turn out a series of ships with much more regularity than others. Being the lead yard or making many ships of a kind helps but is not conclusive. The extra regularity shown by one yard compared to another may reflect better planning, more awareness of schedules, more willingness to suppress other concerns in deference to schedule or space constraints, or other factors. The regularity probably resulted in more efficient and predictable use of facilities and people, and may have contributed to the learning. Sometimes, delivery dates are negotiated and thus reflect other factors besides the yard's production capabilities.

One more pair of charts, Figure VI.C. 9 & 10, gives some insight into the distribution of manpower during one ship's construct on. The data are a combination of Figure 6 from "Toward More Productive Naval Shipbuilding" plus some data from other sources. Figure VI.C.9 compares cumulative manning data versus cumulative time in the yard. Comparing the 1960's to the 1980's data, keel laying comes later in the process, reflecting increased preoutfitting, whereas launching still occurs at about the 60% time point. Between 50% and 100% more work has been done by launch time on the 1980's ships compared to the 1960's ship.

Figure VI.C.1O reveals significant differences between the manning patterns. This Figure approximately represents manpower activity or density. The 1960's ship is characterized by a frenzy of activity in the last 20% of the time. One of the 1980's ships shows an orderly application and withdrawal of manpower in what is clearly a planned pattern. The other 1980's ship shows an unsuccessful attempt at this orderly pattern followed by a frenzy at. the end. This indicates that different yards have different success at managing the construction process, even in the 1980's when Japanese methods are allegedly in wide use. (It is typical of manufacturing to find wide differences in productivity between the most and the least efficient firms in any one industry.)

Time data on an even shorter time scale are shown in context in the chapters on ventilation and piping. These data show, for

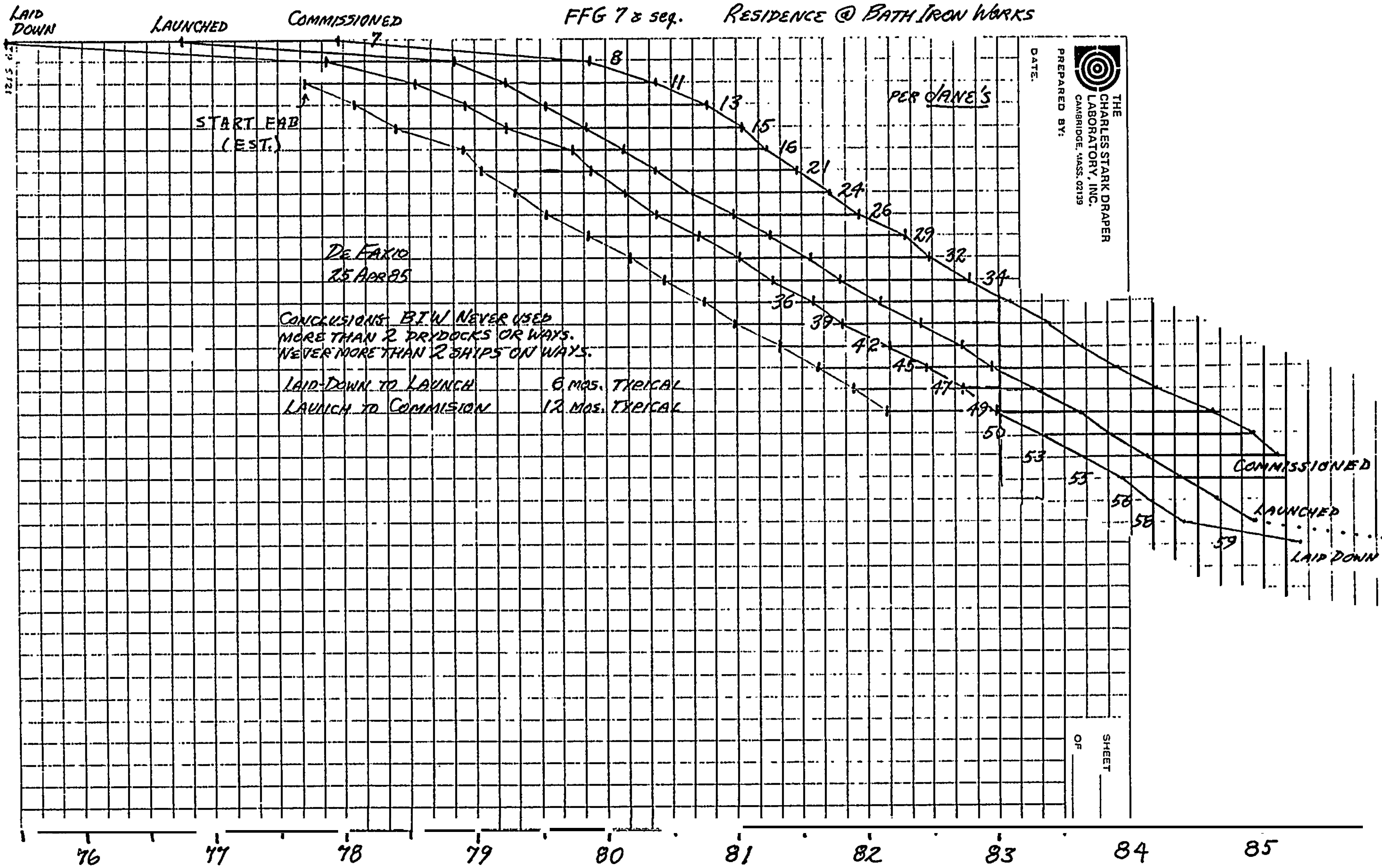


Figure VI.C.4. FFG7 and Follow Ships - Residence at Bath Iron Works

Figure VI.C.5. FFG7 Class Residence at Todd Yards

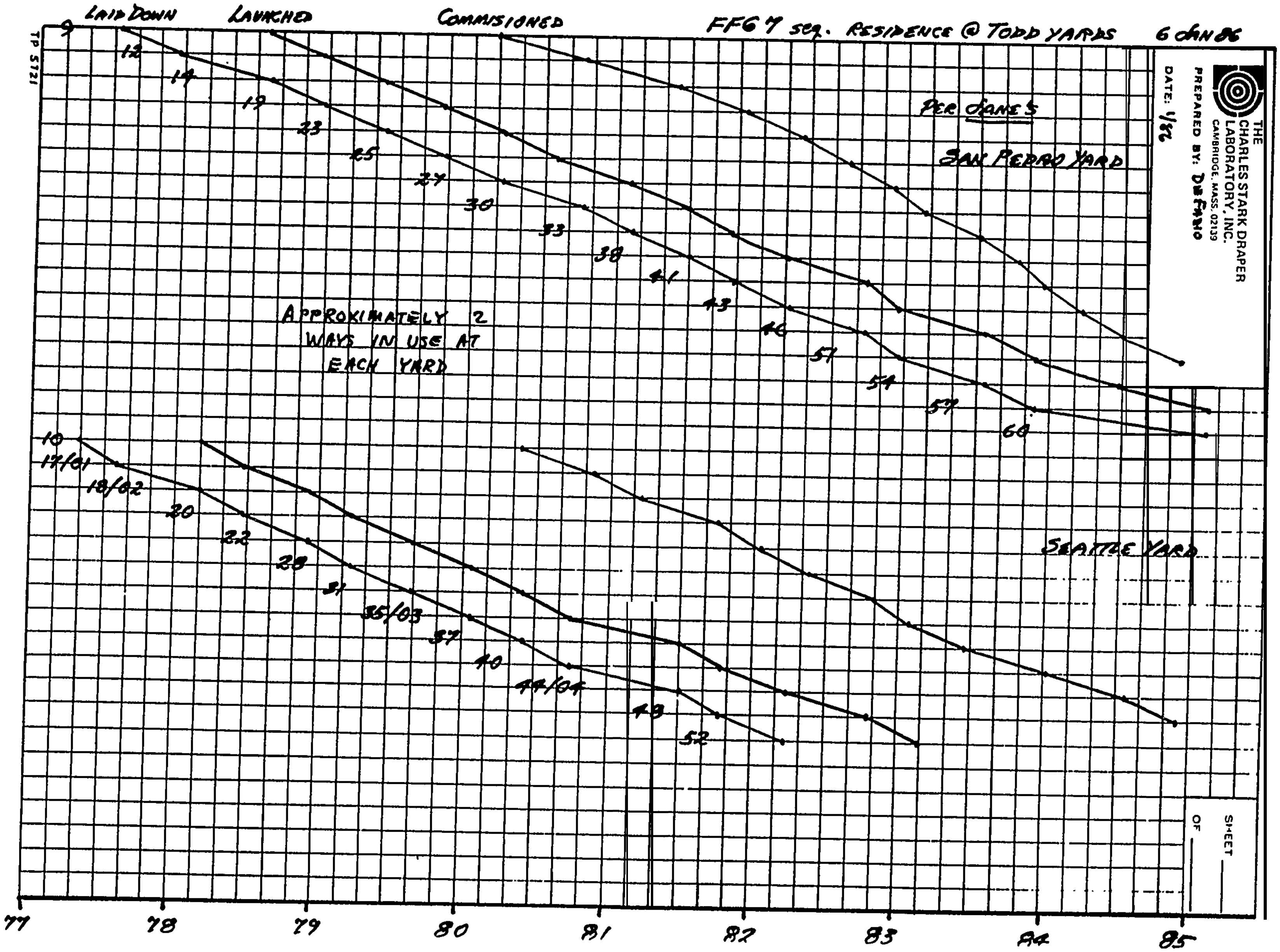


Figure VI.C.6. DD963 Class Residence at Ingalls

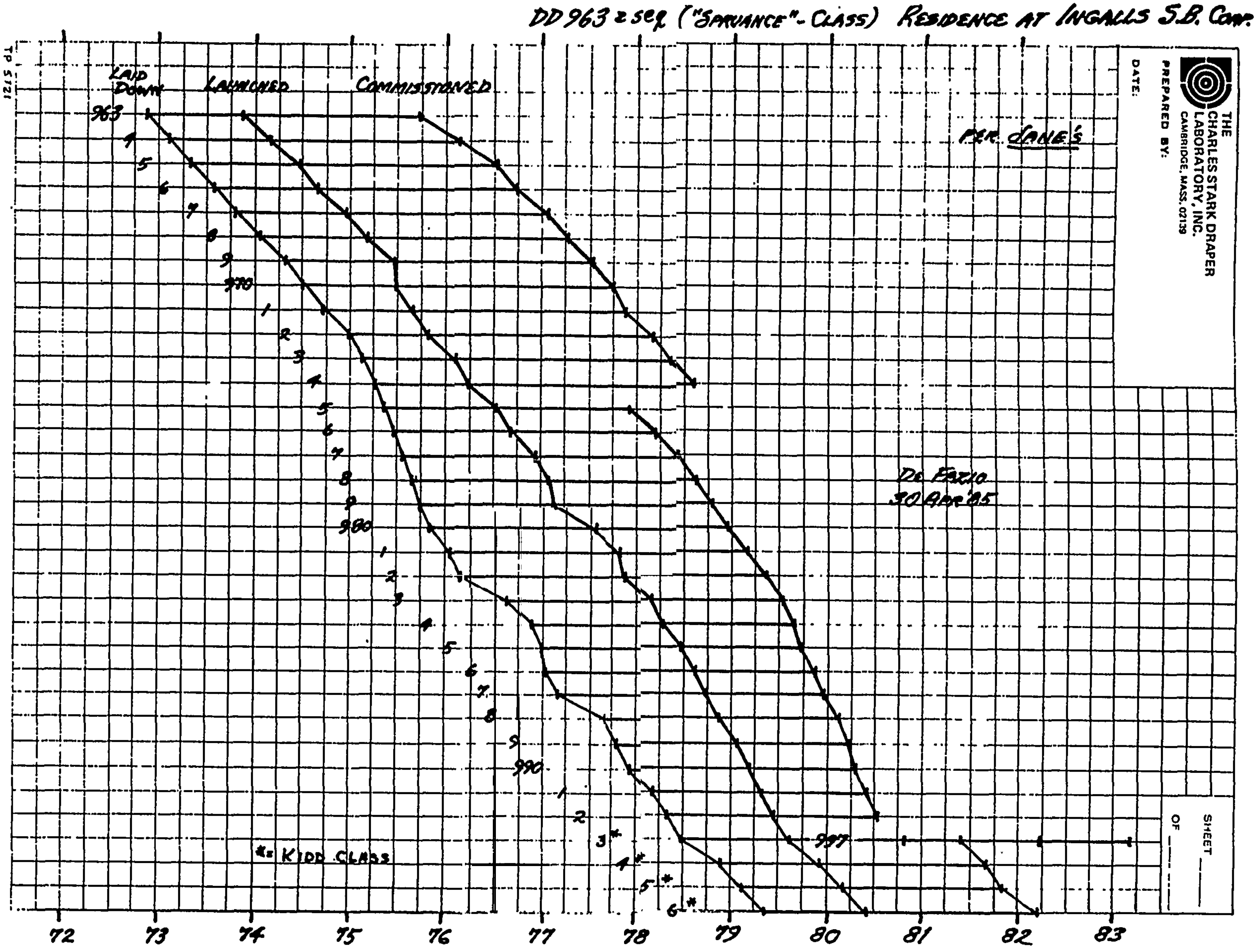
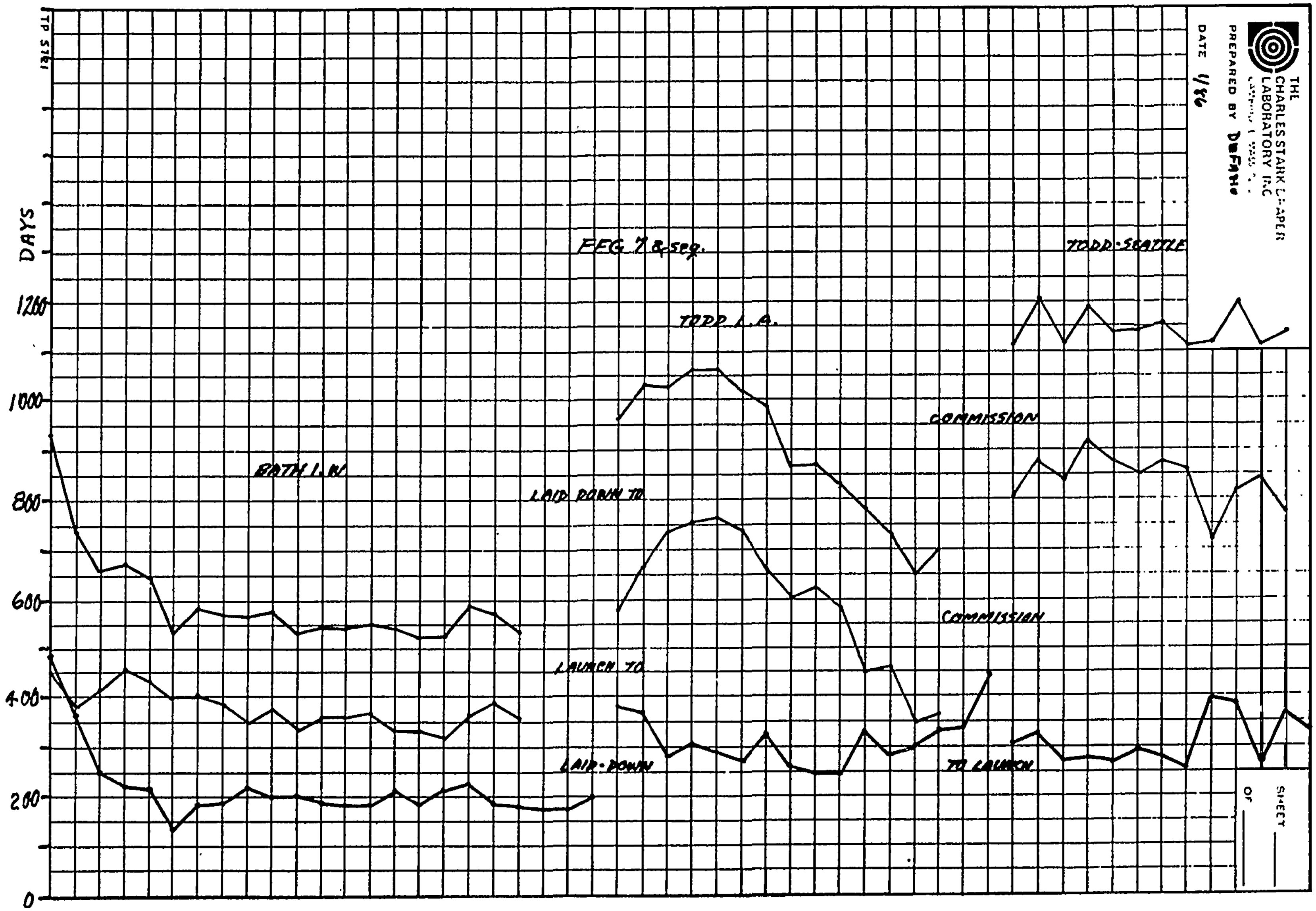
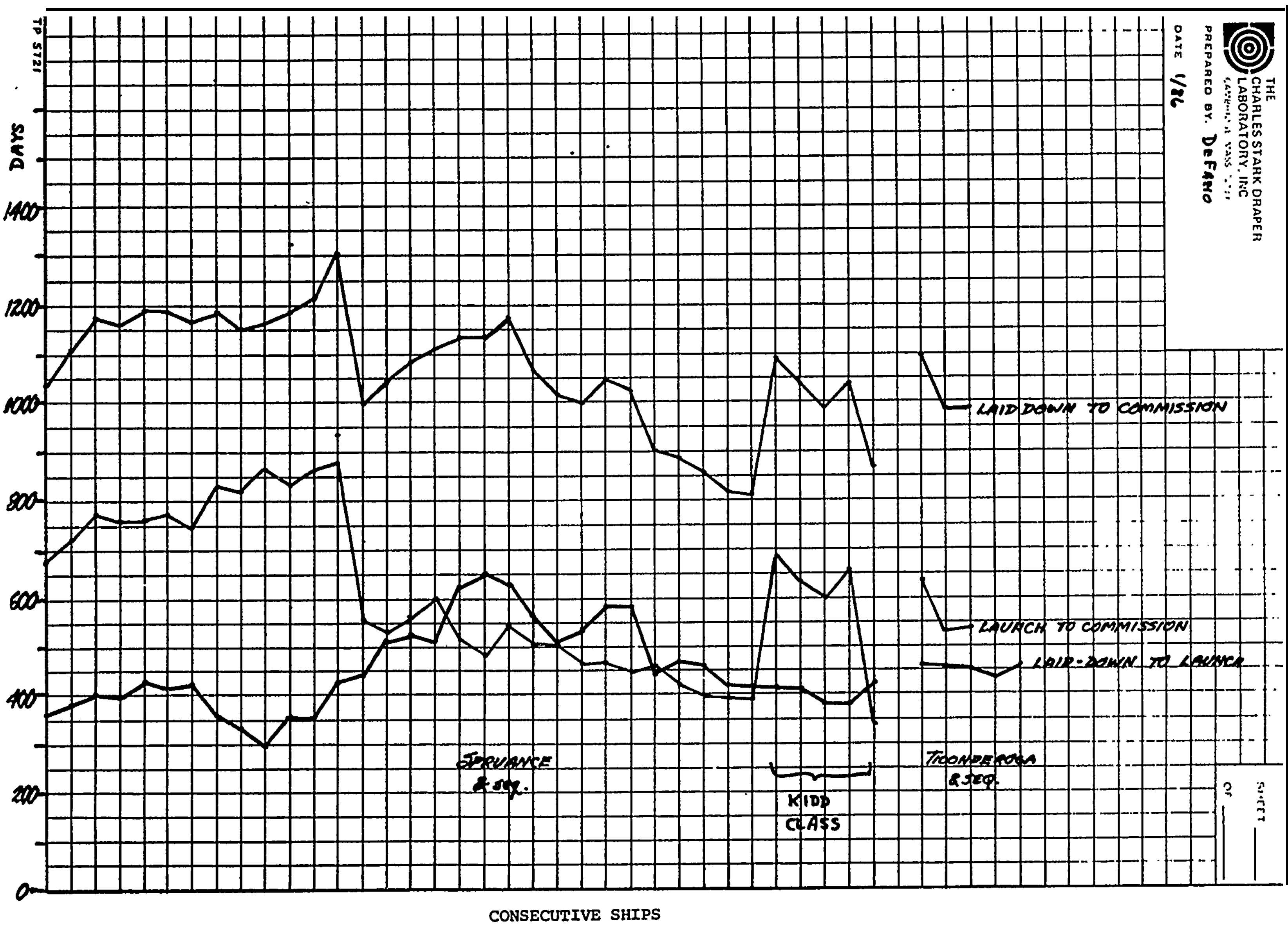


Figure VI.C.7. Total Days Residence and Other Residence Data vs. Consecutive Ships at Bath, Todd LA, and Todd Seattle



CONSECUTIVE SHIPS

Figure VI.C.8. Total Days Residence and Other Residence Data for Three Classes of Ships at Ingalls



example, that in one yard:

> Each man-hour of either a pipe fitter or sheet metal worker is accompanied by 0.25 man-hour of a welder.
>
> Installation hours charged to a typical piece of ventilation is 2.7 times larger than time charged to making it.
>
> Installation hours charged to a typical piece of pipe ranges from 3 to 11 times the hours charged to fabricating it, depending greatly on which pipe system the piece belongs to.

(Data were derived from actual job order charges for one ship from 1980's. Data represent 50 to 100% of total hours charged to the respective categories and are thus believed to be representative. Each job order probably contains dozens or hundreds of vent or pipe pieces.)

These data confirm the well-known difficulty of installation. Together with other data in this section, they emphasize the need to be able to plan the outfitting activity very carefully. This need in turn supports the conclusion that automation solutions or aids for planning should be sought.

D. Conclusions

Design clearly influences not only the performance of a ship but also its producibility. Typically design is done in a rising crescendo that rushes decisions during contract and detail design, when the influence on producibility is the highest. In the case of a multi-ship class, the cost implications of design-producibility decisions extend over many years. Since design cost is amortized over all ships in the class, we say that the design decisions have high leverage. A qualitative case can be made that more design time and money, if it saved production time or money, would be worthwhile.

The same high leverage argument can be applied to planning, although at least some of the amortization would be over the ships made at each yard rather than over the whole class. Better planning can reduce time, cost, and confusion, and can improve utilization of people and facilities, allowing more production for the same facilities and more learning opportunities for the people.

The costs of shipbuilding are divided very non-uniformly between yard costs and other (mainly GFE) costs. GFE dominates the cost of complex surface ships by about 2:1, indicating that producibility and automation would be fruitful topics for GFE.

Regarding yard costs, these are of course influenced by design. Section VII points out that distortion from welding, which is very costly to remove, is enhanced by the thin shell plate currently in use on surface ships. Thin plate also leads to closer frame spacing, increasing the amount of welding and the number of structural intersections.

Yard costs are also influenced by planning. Note, too, that hundreds or thousands of design and planning decisions are involved, so the influence of each may be small. Only accumulation of many decisions over many years will result in major changes in yard costs. (However, cases of 30% improvement in outfitting costs have been reported when comparing zone-oriented and system-oriented methods.) Major changes in cost could result from major compromises in ship capability. This strategy was used with good effect in World War II.

Finally, it is likely that maintenance and modernization costs will be high, especially for complex ships. The sum of these costs over a ship’s life may exceed the original acquisition cost. Thus rationalization and appropriate automation of these later design, planning, fabrication, and installation processes will also be necessary.

References

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VII. INTRODUCTION TO SECTIONS ON SELECTED TARGETS

A. Motivation

This section provides an introduction to Sections VIII-XI which deal in detail with several selected automation target areas. These areas are planning, structure, pipe, ventilation, and economic tradeoff analyses. Omission of other possible targets does not imply that we found no opportunities there but rather that we concentrated our resources on these targets during the study. The economic rationale for choosing these targets was given in Section III.

The sections which follow are intended to serve two purposes: first, they delineate a recommended pattern of study that we have found successful on industrial products; second, they offer some specific suggestions for productivity improvement.

B. Method Followed in specific Studies

The pattern of study follows from the assumptions about the overall method we employed, namely that automation is a system problem and that all avenues need to be examined. This is especially true in shipbuilding where the usual conditions that favor automation are not often fulfilled. AS noted in Section III, there is little work that is truly repetitive, there is not enough process knowledge and economic data, and most items have not been designed for automation and are technically infeasible as designed. This means that a great deal of work is required to successfully automate shipyard operations. One must study design, the product's intended function, the specifications, and various institutional factors, in order to be able to suggest technically and economically feasible redesigns or automation systems.

Our study of each target area comprises most or all of the following topics:

1. What are the technical goals and constraints on the item in question? Study activity included reading texts and reports, and interviewing authorities. These constraints limit the extent of possible redesigns. occasionally we discovered that there was disagreement about the goals or constraints, or that they had been set arbitrarily, or years ago, or by best guesses, indicating that definitive knowledge is unavailable. Under these circumstances one does not know what redesigns to suggest.

   It is common in manufacturing that an attempt to automate will include the first real attempt to understand the process or product being automated. Prior practices may have been surprisingly haphazard or uninformed. Either automation will fail in such a case or else the missing knowledge will have to be obtained. Automation thus acts as a powerful spur to gaining control over processes and designs.

Each of the areas we studied turned up examples of such knowledge gaps.

2. Where in the complex of designers, planners, customers and workers are the criteria set, materials chosen, dimensions and tolerances established, procedures written, data taken or analyzed, and so on? Manufactured products are usually simple enough that a few tens of people design items that are made in thousands. The reverse is true in shipbuilding, where thousands of people contribute to items that are made in tens. The decisions are thus widely dispersed over time and geography, making it difficult to track them down. But

finding out who decides what is an essential ingredient in managing change to better methods. Study activity included background reading and interviews with personnel in design agencies and yards.

3. What are the current methods for designing and making the target items? This establishes a base line from which changes can be suggested. Surprising variations can be found from agent to agent or yard to yard in detailed planning, design, and functional task execution, even on identical or similar ships. Examples include:

   outfit strategy
   structural module shape
   vent fabrication
   equipment calibration
   tolerances achieved
   amount of similarity between jobs that is recognized and exploited

   Study activity included background reading and visits to yards.

4. What concrete changes or improvements can be made, in the opinion of designers, workers, or investigators like ourselves? What improvements have been suggested in the past or used in foreign yards? We found that many suggestions are made but few are adopted. Most of the ideas that occurred to us had been suggested before. Study activity included interviewing authorities and practitioners, travel to foreign yards and machine tool shows, background reading, brainstorming, and inquiries to industrial firms that offer various processing equipment.

C. Possible Targets Not Pursued

Several promising study areas were identified but not pursued deeply during this study. They are foundations, measurement methods, and planning and outfitting aids.

Foundations are an attractive target for process lane work and possible automation. Each ship contains hundreds or thousands. In some cases there is some standardization. Many foundations are small enough that compact machinery might be feasible. In some cases, such as electronic equipment, fabrication and assembly methods other than "cut apart/weld together" might be feasible. Hangers for pipe, wire and vent are little foundations and may be possible targets as well.

Measurement methods are essential to any long term rationalization or automation program. They are explicitly called out on the Flexible Automation Logic diagram in Table IV-1. Systematic measurement and recording of measurements are not widely practiced in U.S. shipyards. Until this changes, there will be only limited progress in flexible automation. Necessary developments include instruments, reference datum lines on tie ground, reference marks placed on parts, and near real time data recording and feedback to process improvement methods.

Planning of outfitting and outfitting itself are both essentially manual and experience-based. New computer tools allow a designer or planner to visualize the outfit items in a zone but there are no decision aids on the computer. The designer thus has only a convenient version of the conventional plastic scale model. Possible decision aids include routines to find equipment removal routes, search algorithms that find good outfit sequences, and accuracy control algorithms that recommend sequences of welds or assembly steps to minimize error propagation. In the fields of architecture, city planning, robotics, and artificial intelligence, similar problems have been studied and transferable results may be available.

D. Other Possible Areas

During this and other projects we have noted ongoing efforts or opportunities in painting, surface preparation, cleanup, and other similar activities. We devoted no effort to these.

Another area not usually considered in conventional shipyard automation studies is system test and checkout. Little help can be expected from foreign commercial shipbuilders. Yet the time between launch and delivery of a combat ship is heavily devoted to this activity. We know that Navy ship and aircraft repair facilities have automated test equipment. However, this equipment is often unavailable for new weapons systems and often must be created by detective work and reverse engineering due to lack of original data and specs. Here is another example of an institutional problem that contributes to lack of automation.

E. Summary

This section described the methods used to study four target areas that are detailed in the next four sections. Brief discussions were also presented on several promising topics that were studied either briefly or not at all, but which deserve further work.

VIII. FLEXIBLE AUTOMATION POTENTIAL IN STRUCTURE

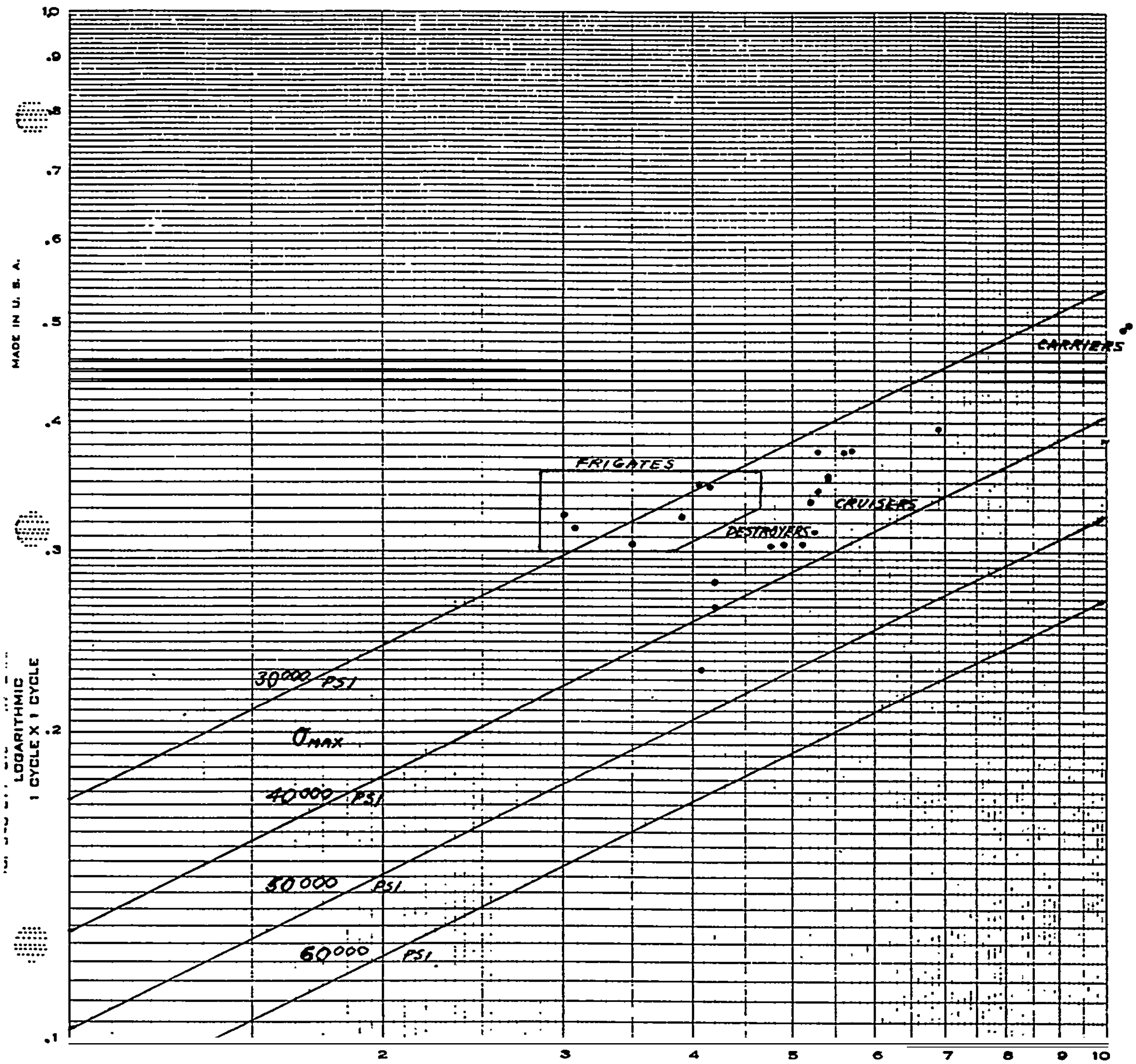
Introduction

One can consider the automation of many of the tasks that are involved in the production of structure, such as preparation of materials, cutting, blasting, and priming; layout; seam-welding; cleaning and slag removal; snagging and grinding welds and edges; placement and welding of details; bending and shaping of . structural elements, &c. Indeed, automation of many, perhaps most of these tasks has been addressed and in many cases implemented at various times in various yards, and on various ship types and classes. Clearly task automation is not always suited to all cases. Economics in production of structure may be gained not only by means of task automation but also by reduction in rework, and potentially, by structural design refinement and simplification. Reduction in rework requires some accuracy-control and calibration efforts, and design refinement seems to require new or better structural information.

A. Design of Ship’s Structure

Shipts structure is a very large fraction of a ship's displacement. For a surface combatant of length upward of 300 feet, weight of structure accounts for typically one-quarter to one-half the laden displacement of the ship, the larger fractions associated with the longer ships (Figure VIII.A.1). For example, structure represents about 0.34, more than one-third, of the laden weight of an FFG-7 class frigate, and about one-half the laden weight of a modern carrier. An immediate conclusion is that all aspects of a ship’s structure are critical and that no aspect of structure can afford the attention of a heavy hand, not in design, not in materials, not in workmanship, and not in quality control. Structural design and construction are very tightly constrained.

For example, if, to accommodate a more economical welding process, plating and framing thicknesses would have to be



LENGTH, 100 FT

FIGURE VIII A.1

SOURCE: TECHNOLOGY TRENDS FOR HULL STRUCTURE DESIGN OF U.S. NAVY SHIPS. BAND, LAVIS & ASSOC, INC. (MD) JUNE 1982 (DATA POINT ONLY) increased by one-tenth (10%), an immediate consequence would be a corresponding one-tenth decrease in the total weight of all other systems in a modern aircraft carrier; propulsion, aircraft, ordnance stores, fuel, manning, communication, command and control, and so forth. The alternative would be an increase in displacement. If a heavy system, such as propulsion, cannot be made lighter, a greatly disproportionate weight-reduction requirement is imposed on remaining systems, such as fuel, aircraft, and ordnance stores, if displacement is to not change.

The point is that a ship’s role, mission, endurance, and effectiveness are all critically affected by changes in structure. In such an environment, any change offering small improvements in productivity must be considered in terms of its effect on structural weight, and such changes in general will be unacceptable, especially so for big ships, if even small but widespread weight increases are involved.

Such high weight sensitivity highlights fastening technique, typically welding, in ship construction. For example, if welds in plate or in longitudinal do not develop the strength in tension of the parent material, or result in locally greatly deviant bending stiffnesses, *or* in locally great residual stresses, the design is flawed in the sense that nearby parent material will be underworked (and too heavy) in the case of insufficiently strong welds or overworked, say, in the case of an excessively stiff welded region.

Thus the criticality of all aspects of ships' structure: design, materials, manufacturing, geometry, welding, inspection and quality-control. Especially in the case of surface combatants, the methods engineer is virtually constrained to offer productivity-improving changes that also offer some improvement or no compromise in other aspects of ships’ structure. Such beneficial changes may be available; an example from the automobile industry comes to mind. The automation of the spot-welding process for auto body construction increased both weld location precision and weld-uniformity, allowing a decrease in the number of welds in a line to attain similar function.

Accepting the fact that structure is critical in all itS aspectS, one then asks where there fight be the possibility fOr increasing productivity; by design refinement, by automating a process, or by other means. To address this question, one must explore structural design criteria, constraints, practice, knowledge, and technique.

Figure VIII.A.1 gives structural weight as a fraction of laden displacement for modern surface combatants varying in length from about 300ft to about lOOOft. The *general* trend of variation of structural weight fraction with length is pretty clear. By making a very, very crude model of a ship and applying static wave loading by means of the accepted criterion (h, wave height $\approx (1.1 \sqrt{\text{feet}}) \times \sqrt{L}$, square-root of ship length), one gets constant-stress curves of the form of the lines in Figure VIII.A.1. Clearly the form of the constant-stress lines and the trend of ship structural design are similar, leading to the conclusion that surface combatants are indeed designed, carefully, to the accepted *criterion.* (We should emphasize that the crudity of the model used to derive the constant-stress lines is such that the stress-values associated with the lines do not represent true structural stress values, though the form [slope] and the interval are representative.) More detailed data suggest that the latest surface combatants are more conservatively designed, or more lightly-laden, than their recent predecessors. In particular, FFG7 and CG47 classes occupy relatively high points on the plot; yet, by observation, their plating is thinner and their longitudinal correspondingly more closely-spaced than similar craft of the 1940's or 1950's. The later ships are more exquisitely wrought yet more conservatively placed in the structural design space.

The form of the criterion for (static) loading of a ship's structure in a seaway is itself open to question. The design criterion calls for consideration of a wave of the ship's own length and of height proportional to the square root of wave length. Thus ,

$$h \approx 1.1 \sqrt{ft} \sqrt{L}$$

Wilbur Marks, however, indicates that wave-heights of of fully-developed seas grow much faster with wave-length than root-length; that is:

$$h \approx c\,L^{1.22}$$

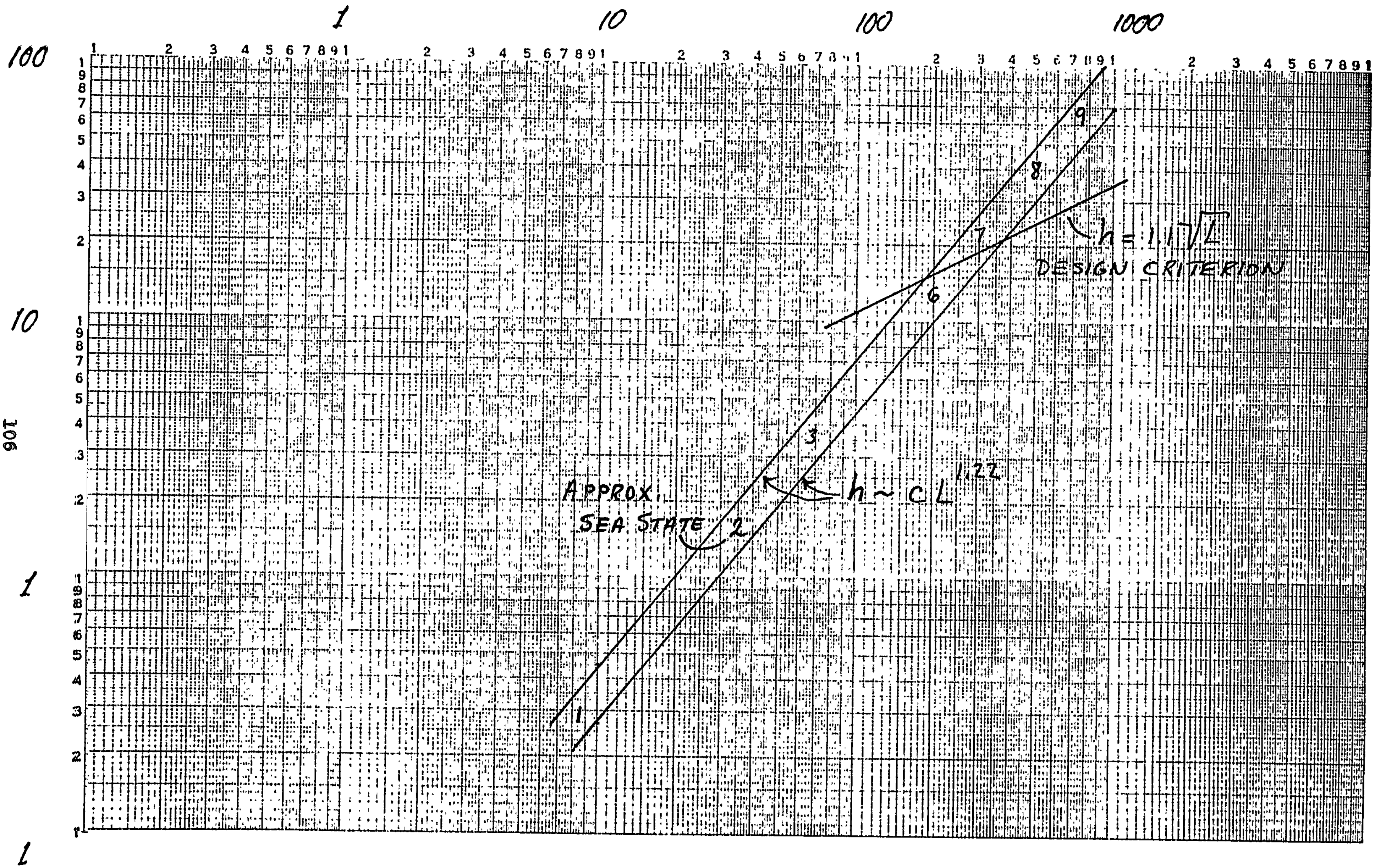
These relations are plotted in Figure VIII.A.2, with a crossover at a ships' length of around 300 feet. It is tempting to conclude from this comparison that, if 300-foot ships are properly served by the design criterion and are well-designed, then longer ships, 1000-foot ships, are not suited to actual developed sea states of above 7; or, if 1000-foot ships are well-served by this criterion and are well-designed, then shorter ships, 300-foot ships, are quite overdesigned.

We are not in a position to know whether the non-coincidence of this design criterion and the Marks wave-length wave-height relationship is a problem for structural design, or if so, where the solutions may lie. It is clear to us, however, that if the seaway design criterion followed the Neumann spectrum given by Marks, then 1000-foot-long surface combatants would not exist; under the revised criterion their structural weight would be too close to their displacement.

This disagreement between wave models, one associated with a design criterion, one associated with developed sea-state, is by no means the only significant uncertainty associated with ship-design and construction. A review of such uncertainties is taken from the Structural Design Manual for Naval Surface Ships (2) and included here as Table VIII.A.1. Of course it is the obligation of the designers, builders, and inspectors of ships to work conservatively enough to accommodate all of the uncertainties. Small changes in one area may have effects in other areas, which themselves may be small or large. An example of such a change might be material control which guarantees more uniform strength and yield properties and fewer defects in the structural raw material. The full benefits of slightly raised strength limits are not realized until welding techniques are upgraded to accommodate the strength increase in tension, and,

WAVE HEIGHT,
FEET

WAVE LENGTH,
FEET



SOURCE: NEUMANN SPECTRUM
WILBUR MARKS, DTMB 1956

FIGURE VIII A.2

WAVE-LENGTH VS. WAVE-HEIGHT
FOR FULLY-DEVELOPED SEAS AT THE
THE RANGE OF SEA-STATES

TABLE VIII A.1.

LOAD UNCERTAINTIES:	o	Simplifications introduced when transforming the actual known environmental load model.
	o	Lack of knowledge of the true nature of actual loads; i.e. loads are dynamic rather than static, oscillating/cyclic rather than fluctuating without sign reversal.
MATERIAL UNKNOWNS:	o	Variations in material properties from those predicted, specified, or assumed.
	o	Presence of impurities, production defects or other non-uniformities.
ANALYSIS SHORTCOMINGS:	o	Inaccuracies or errors introduced when establishing the structural configuration model.
	o	Improper coupling of model and failure mechanism.
	o	Geometrical configuration uncertainties .
	o	Shortcomings of the existing theories of analysis; they largely fail in regions of high structural discontinuity and large deflections.
UNCERTAINTIES INTRODUCED DURING MANUFACTURE:	o	Presence of “residual” stresses and deformation introduced in the course of manufacture through uneven cooling, welding, etc.
	o	Weld defects (voids, cracks, incomplete penetration, lack of fusion, and wrong filler metal) .
	o	Casting defects (voids, porosites, surface defects, evidence of shrinkage, segregation, and internal discontinuities) .
	o	Surface finish imperfections.
	o	Misalignment of structural components.

more fundamentally, until the structural design itself is modified to accommodate the increase in compressional strain level without possibility of crippling, buckling, or other instability.

Indeed there are various limits on the ability of a ship's structure to fully beneficially accommodate material or design “improvements” such as stronger structural steel. For example, to utilize the benefits of stronger steel, the structure must accept excursions to larger compressional as well as tensional strain, which means thinner shell sections and substantially closer spacing of stiffeners aligned with the compressional principal axis. This last requirement, illustrated in Figure VIII.A.3., is a consequence of the thinner shell section, the increased compressional strain, and the need to delay any potential instabilities to beyond increased yield loads. A simple “spreadsheet"-type comparison, based on some very simple assumptions and ignoring some other constraints, is illustrative of the consequences and magnitudes of some changes subsequent to accommodating a change in design stress from 32,000 psi to 40,000 psi. Please see table VIII.A.20 One readily sees that a consequence of fully beneficially absorbing a significant increase in design stress is a more significant increase in the complexity of the ship’s structure, as measured by, say, the length of weld, the number of longitudinal, or the number of structural crossings.

Other previously-unmentioned constraints affect the designers’ freedom to fully beneficially incorporate material design stress increases. Amongst these constraints, which generally put minima on plate thicknesses, are the following:

1. The need to provide specified location-to-location stiffnesses to guarantee alignments within tolerance under load. Examples might be alignments between a phased-array radar unit and a weapons-associated radar unit, between a radar unit and a radar unit and a weapons platform, between a rudder pintle and a fin stabilizer pintle, or between a prime-mover mount, a gearbox mount, and a propellor-shaft tube and strut.

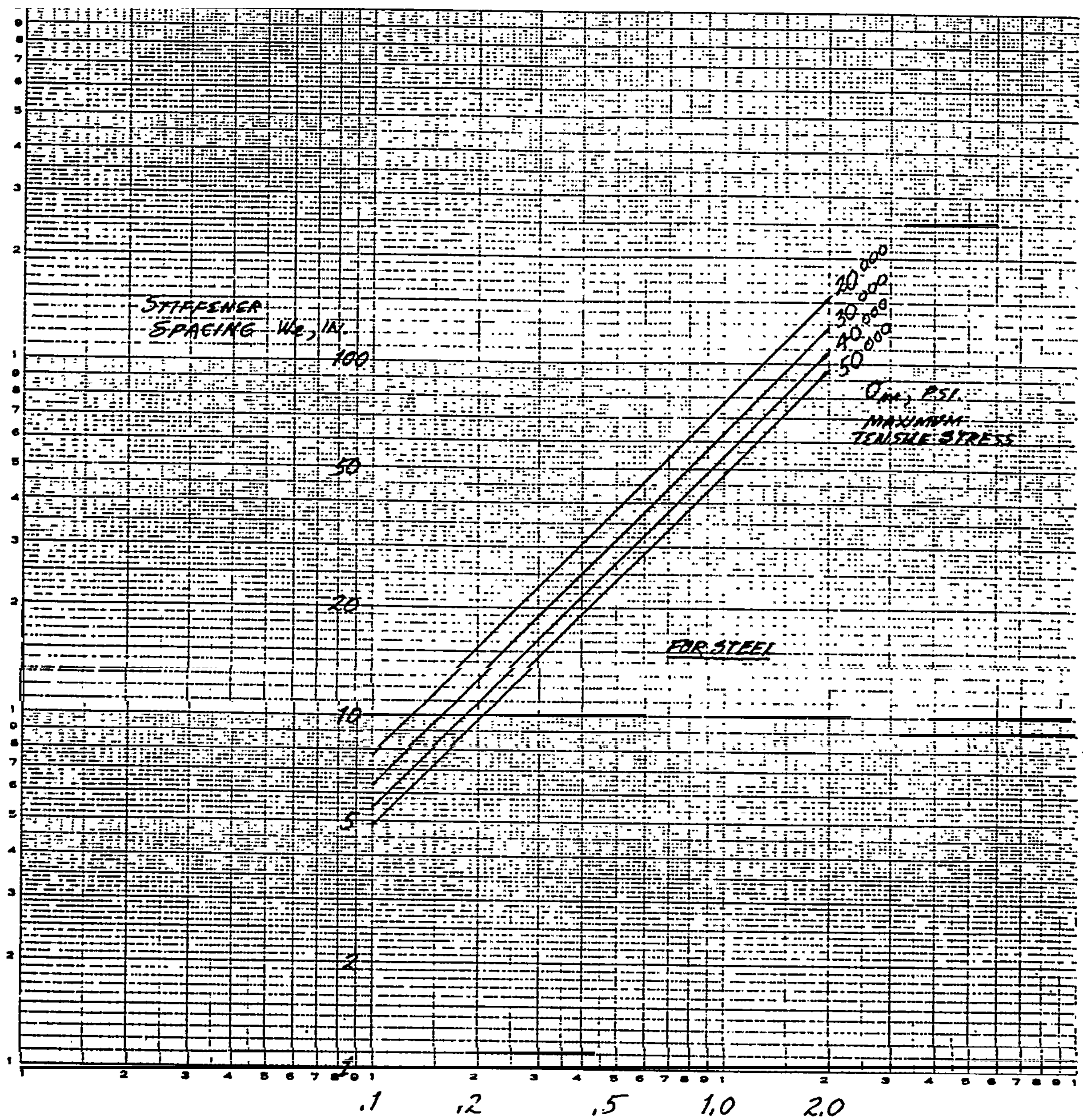


FIGURE VIII A.3

Plate Thickness
t, inches

SOURCE: STRUCTURAL DESIGN
MANUAL FOR NAVAL SURFACE SHIPS

NAVSEA 0900-LP-097-4010
Dec. 15, 1976

TABLE VIII.A.2

ILLUSTRATIVE EXAMPLE - CHANGES CONSEQUENT TO AN INCREASE IN STRUCTURAL STRENGTH FROM 32,000 psi TO 40,000 psi.

	ORIGINAL VALUE	NEW OR CONSEQUENT VALUE	CHANGE FACTOR
Design Stress Level	32,000 psi	40,000 psi	1.25
Design Strain Level	.00107	.00133	1-25
plate Thickness	5/8 in	1/2 in	(1/l.25)
Spacing of Longitudinal	38.3 in	27.4 in	$(1/1.25)^{1.5} \sim .7155$
Structural Crossings	n	1.95 n	$(1.25)^3 \sim 1.95$
$W_{SRR}/W_{\Delta FL}$ (Structure Weight Fraction)	.373	$\gtrsim .287$	$\gtrsim .77$
Number of Longitudinals	m	~ 1.4m	$(1.25)^{1.5} \sim 1.40$

2. The need to limit welding distortion, which is dependent on many variables including weld-rod Size and plate thicknesses.

3. The need to provide local dent-and puncture-resistance at various locations in anticipation of contact with tugs or other craft which may come alongside, with wharves or docks, with shorings and stand-offs during dry-docking, and even with bottom-contact.

4. The need to provide resistance to piercing by a range of ballistic fragments of various sizes and velocities.

Still other design constraints exist. One which affects material choice is the need to provide means of arresting rapid crack-propagation. In riveted ships this had not been an issue and many earlier welded ships incorporated riveted strakes for this purpose. Modern ships with structure that is a welded monolith often depend on strakes of high-yield steel which, while difficult to weld, is relatively resistant to rapid crack propagation.

The foregoing is a quick description of the ships' structural design environment. A summary of some salient features of this environment includes the following points:

1. Structural weight is a large fraction of a ship's displacement. Widespread changes, even small ones, in a ship's scantlings or structure have a potentially large effect on a ship's performance as measured by range or cargo or speed or stores.

2. Structural parameters are typically heavily interrelated so that a change in one parameter generally requires changes in other structural parameters to maintain a balanced, elastically stable design.

3. Creation of ships’ structure is beset by significant uncertainty, which the designers must accommodate, occuring at all levels. Uncertainties exist in the loading criteria, the material, the design analysis, and in the manufacture, the welding, and the realized geometry.

4. Structural design involves accommodating many sorts of loads beyond simple hydrodynamic loads, and satisfying real constraints on various structural parameters. Thus the structural designers’ design freedom is in many details limited.

Considerations of means to increase productivity or to automate tasks or processes involved with creation of ships’ structure must then be evaluated in the light of such a constrained design and construction environment. Such means may be very effective if they can produce process improvement as well as increases in productivity. Clearly, however, there is little room in ships' structure for small compromises or trade-offs in the sense of small productivity gains at the cost of small increases in scantlings or plate thicknesses.

B• Increasing Productivity in Creating Ships' Structure

There are many areas in the creation (design and construction) of ships’ structure where there is the potential for improvements in productivity or for improvement or automation of processes. There have been many attempts of task automation where the potential has existed, of course with varying results. Success and suitability have depended on many matters including aspects of ship’s design, ship’s specification, material requirements, material choice, and planning decisions regarding build sequence.

A group of issues that bear on productivity and automation potential are listed in a table and subsequently discussed (see Table VIII.B.1.). For convenience, these issues are divided into three generic categories; namely, knowledge issues, design issues, and construction issues. Knowledge issues have to do with resolving uncertainties which ultimately affect design. There

TABLE VIII. B.1 ISSUES THAT BEAR ON PRODUCTIVITY AND AUTOMATION POTENTIAL
Knowledge Issues: Design Criterion for Ship in Waves - Wave Height Structural Member Intersections - What happens physically, are collars needed? Welding Heating, Distortion, Residual Stresses, and Relief. Local Structural Stability - crippling, tripping, brackets, structural details. Interactions - Welding, Line heating, distortion, material properties, stability. Non-Hydrostatic Loads - Wave-slap, impact, wharf, drydock, tug loads.
Design Issues: Design philosophies - Grand Compromises "No-Frame" Concept. Inverted "L" (Angle or Bulb-Flat) Longitudinals. Simplified Heavy Structures Design of Structural Member Intersections. Design of Tripping Brackets, Lugs, and Structural Details. Design Geometry for Easier or Automated Welding.
Construction Issues: T-Beam Production. Beam-Bending Reduction in Fitting and Rework Cutting Neat. Accuracy Assurance, Accuracy Control. Geometry Control, Measurement, Verification. Welding Distortion Issues Welding Sequence Tacking, Staggering Welds, Temperature Control. Prediction of Distortion. Rectification of Distortion. Welding Technique Issues One-Side, Two-Side, Backing Technique. Chipping and Cleaning. Grinding and Finishing. Inspection and Welding Quality Assurance.

are, for example, details of design practice or actual design which affect productivity adversely, said details being based on shaky or incomplete fundamental knowledge but properly accepted on the basis that a history of use of said details has been successful in ships at sea. It would be risky, even foolhardy, to change such details without basing such changes on new or enhanced knowledge; hence, knowledge issues. The design issues category and the construction issues category are presumed not in need of explanation.

1. Knowledge Issues

a) Wave Height Model

The question of a wave-height model for consideration of ship beam-loading is perhaps the most fundamental issue we have found as the wave model has first-order effect on a ship's nominal loading, structural design, and scantlings. The issue, as outlined in Figures VIII.A.1 and A.2 is that ships are designed to particular wave-height models and that there is more than one such model. Existence of several models may indicate issues beyond our understanding, or may indicate uncertainties which could beneficially be resolved. Several wave models are plotted in Figure VIII.B.1. At least two have been used as design criteria; the model labeled "Biles" was advocated by Hovgaard in "Structural Design of Warships" decades ago, and Figure VIII.A.1. is evidence that the model labeled "designed criterion" is in recent use in warship design. The dotted line in the Figure VIII.B.1. is a wave parameter with length dimensions used in structural design of ocean-going steel ships to ABS standards; it is not clear to us whether it represents a wave-height model. Interestingly all the models are in fair agreement for wave lengths of around three-hundred feet. It is clear, however, that if the Neumann Spectrum is realistic, large ships designed according to the design criterion are much less conservatively designed than small ones. It has occurred to us that the progression from the older Hovgaard criterion to the less

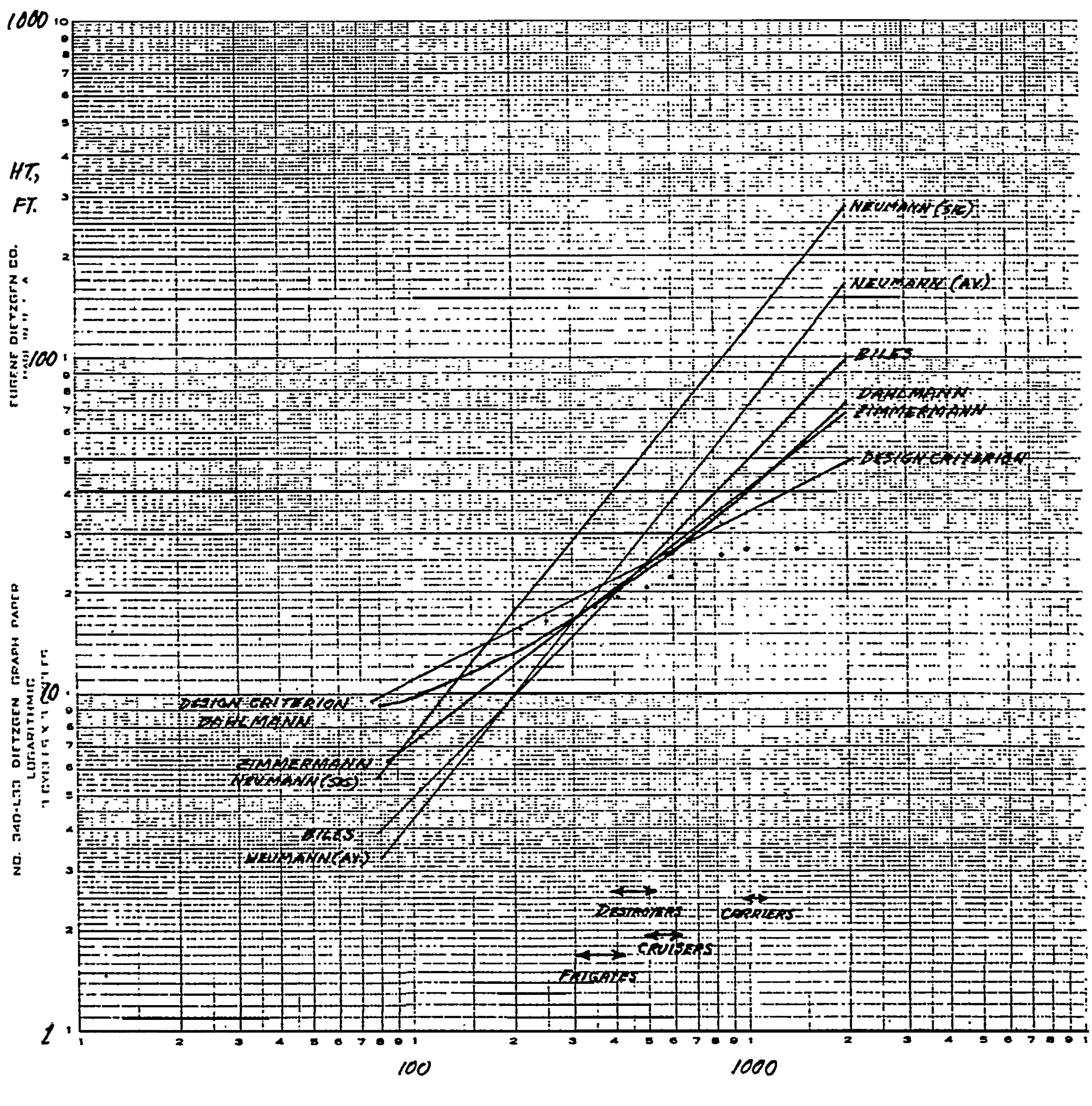


Figure VIII B.1

Different Models of Wave Height vs Wave Length conservative (beyond 484 feet) currently-accepted criterion may represent the effects of new knowledge. However, the current existence and use of two criteria, one by the Navy and one by ABS, seems to represent to us some uncertainty which, if resolved, many have beneficial effects on either structural integrity or productivity of structure.

b) Structural Intersections

The matter of structural intersections; that is, intersections between transverse members (frames or bulkheads) and longitudinal got our attention early. When longitudinal are of "T" form, such intersections invariably involve small welded-in-place structural addenda called collars. Since there are lots of intersections, there are lots of collars. In the case of bulkhead crossings, collars also serve a non-structural requirement. They complete the bulkhead's watertight closure at the longitudinal and are thus serve an indispensable function. In the case of frame crossings, it is not clear to us which or what purpose they serve or whether they always are needed. Clearly great savings could be had if one collar would serve where there are now two, or none would serve where there are one or two. In asking structural designers and naval architects about the purpose of collars at frame crossings, we have had the following answers:

1. TO replace the material, loaded in shear, removed from the frame.
2. To unload the "Knife-Edge" forces between frame-web & longitudinal-web.
3. TO serve as a tripping bracket for the longitudinal.

Clearly, in particular cases, at particular crossings, collars may be serving any two or all three of these purposes. It seems to us, however, that each of the above purposes except the first, replacement of frame shear web at the longitudinal, can be served by a simpler design and that the first issue is virtually no issue at all in the case of deep-frame designs. Whether frames are deep or not, welding the flange of the longitudinal to the web of the frame obviates any need for a tripping bracket in the region of the crossing. Unloading the “knife-edge” forces between crossing webs can be more simply addressed by, say, drilling the frame web above the longitudinal web as shown in Figure VIII.B.2i. In any event, we have observed installation of collars, of the sort shown in Figure VIII.B.2a but of such narrow breadth that they could not serve successfully either of the first two functions listed above. Since the third function was accomplished by welding of the longitudinal flange to the frame web in these cases, it is our feeling that we may have seen unnecessary collars.

Recommendations regarding collars include the following. That the need, if any, and purpose of collars at each structural crossing be known to the detail designers, by whatever means appropriate; analysis, convention based on loading, standards. That the design of the collars, if any, for each structural crossing be the simplest that will *serve the* need. That the collar.needs at each crossing be explicitly conveyed by drawing notation, codings, or listings to the necessary yard functions by the detail design. Yard functions here include not only those persons who are responsible for structural erection and inspection but also those who schedule, manufacture, and distribute small plate parts. One notes here that welding is called out in such a fashion; that is, explicitly on erection drawings and by an accepted code rather than by pictorial representation.

One can imagine forms of automation which can place and weld structural details, especially in cases where design and dimensions do not change or change in simple, structured ways from crossing to crossing. One may note that such automation may be more suited to the mid-ships sections of slab-sided ships than to surface-combatants. One would also note lesser use of collars in slab-sided ships, the consequence of design accommodations such as bulb-flat (angle) longitudinals, conformal slots in frames to accept longitudinal, and frame tabs that reach the longitudinal flange as in Figure VIII.B.2C.

STANDARD TECHNIQUE

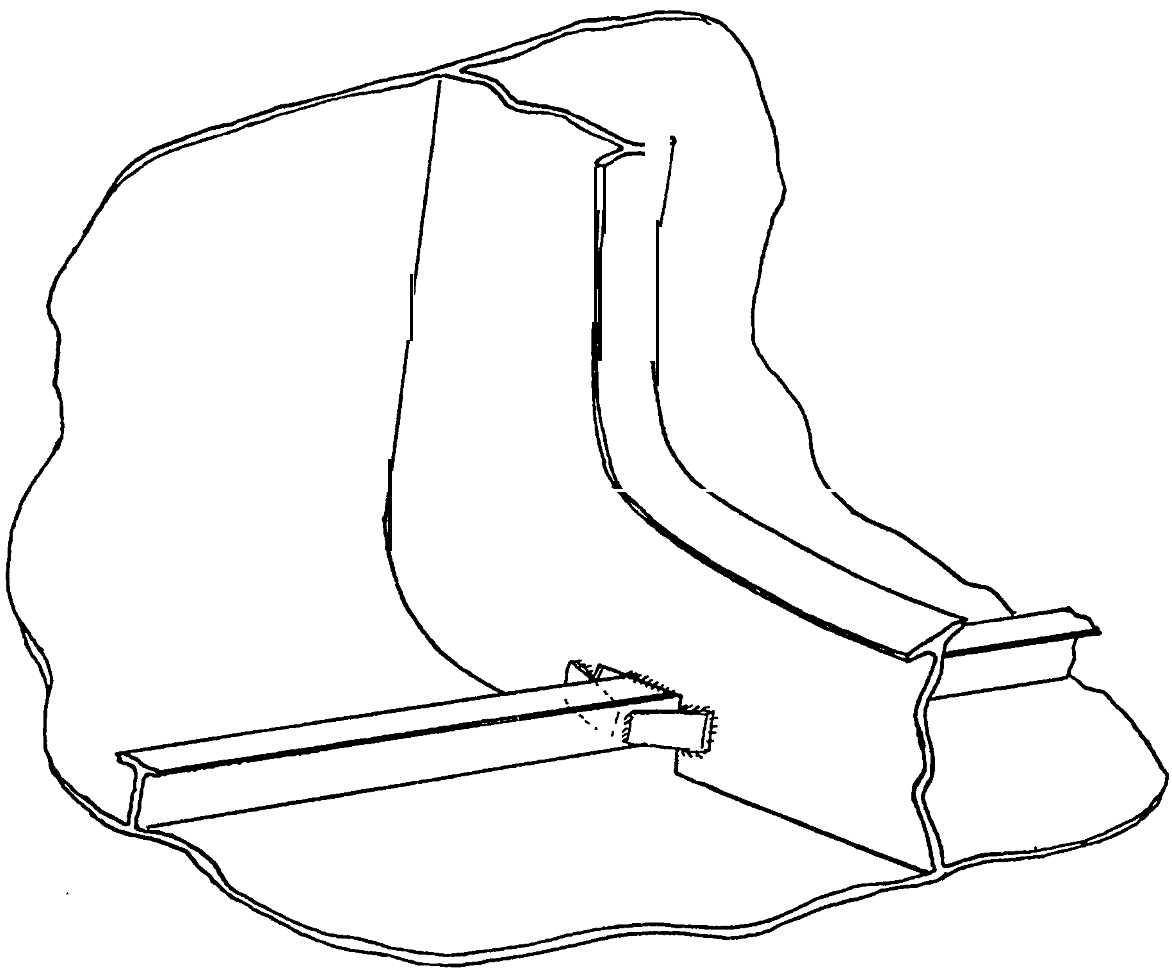
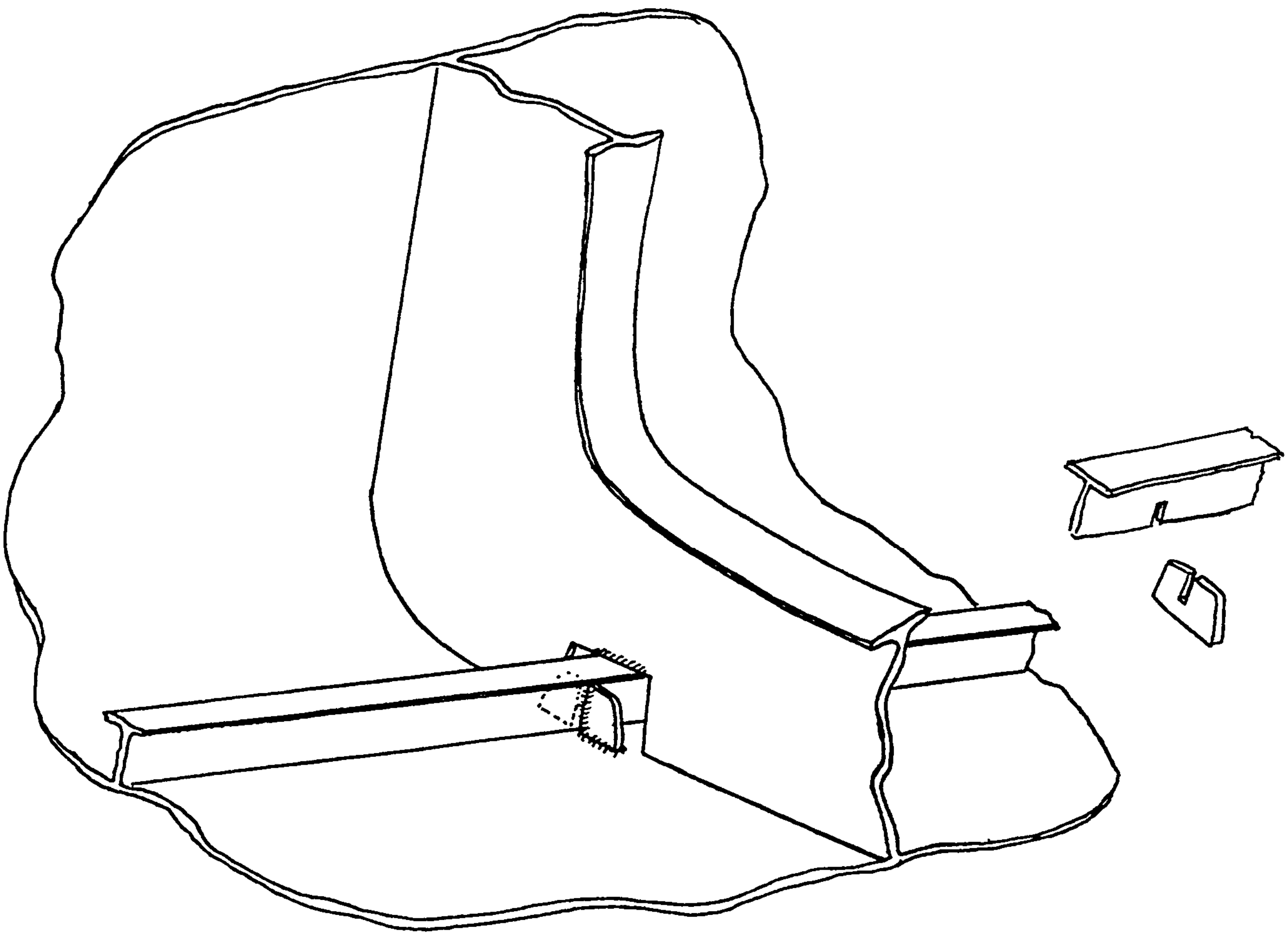


FIGURE VIII. B. 2a

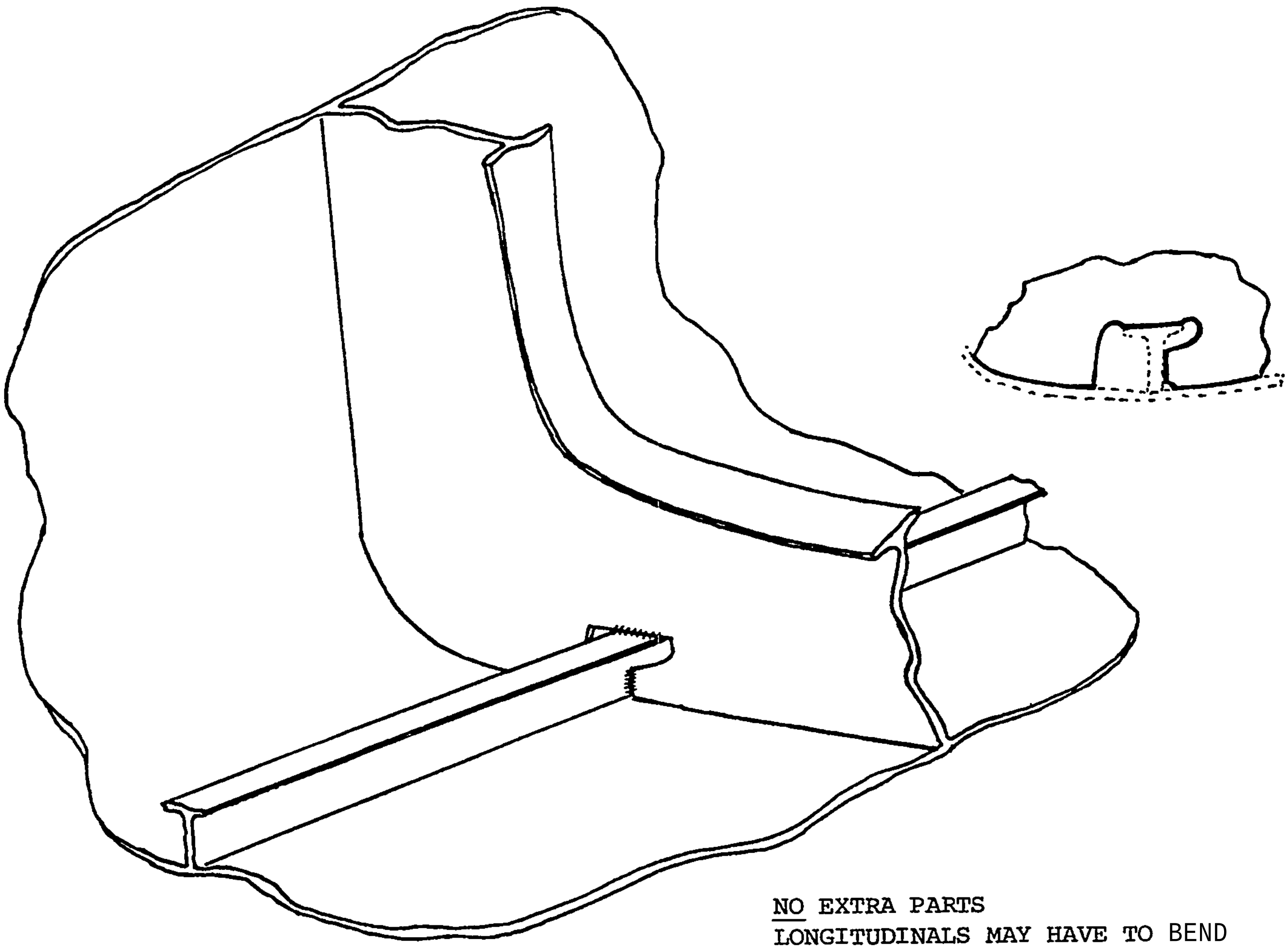
ALTERNATE TECHNIQUE I



SYMMETRICAL (wrt. Long'1)
AWKWARD ASSEMBLY
LOADS PLATE
ONLY ONE PART .

FIGURE VIII. B.2b

ALTERNATE TECHNIQUE II



NO EXTRA PARTS
LONGITUDINALS MAY HAVE TO BEND FROM FRAME TO FRAME.

FIGURE VIII. B . 2c

ALTERNATE TECHNIQUE III

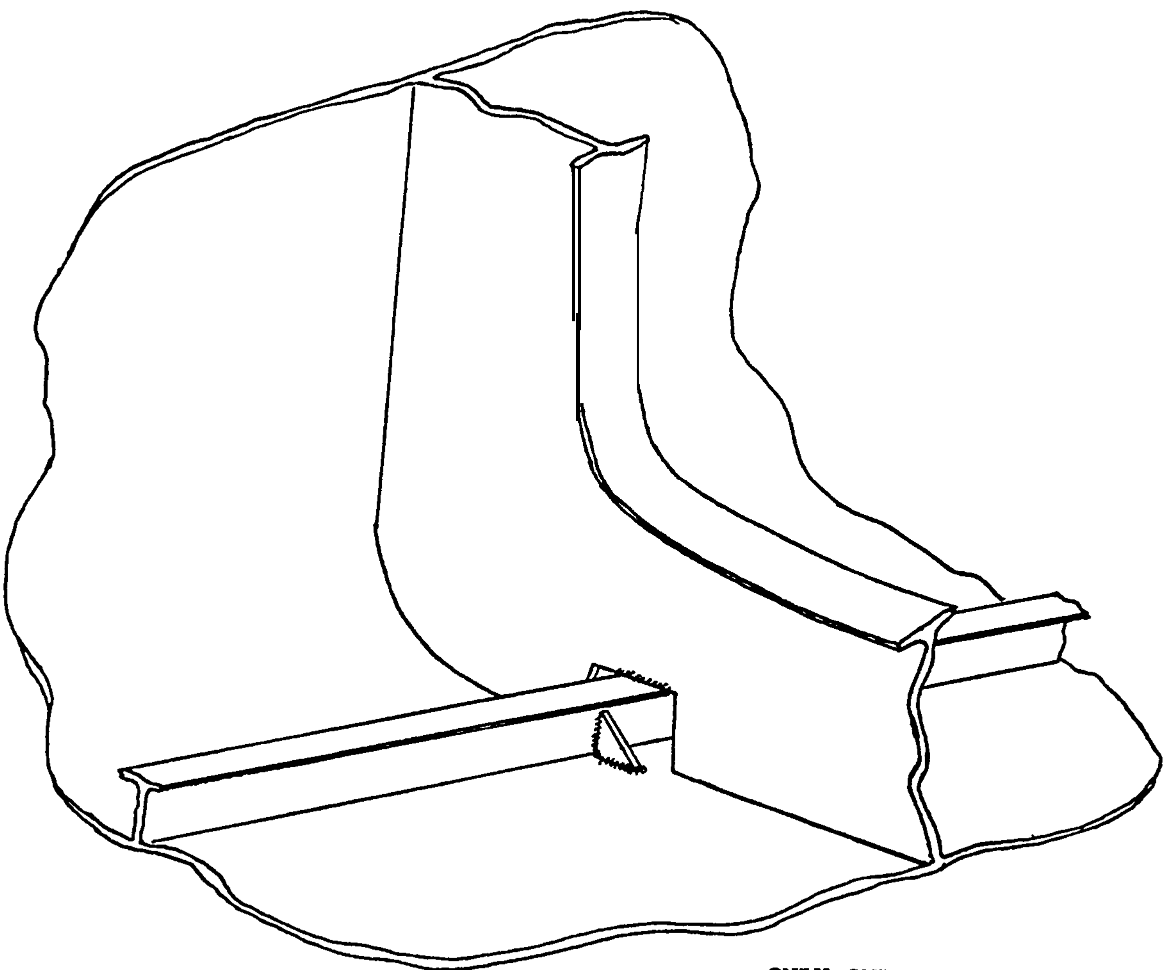
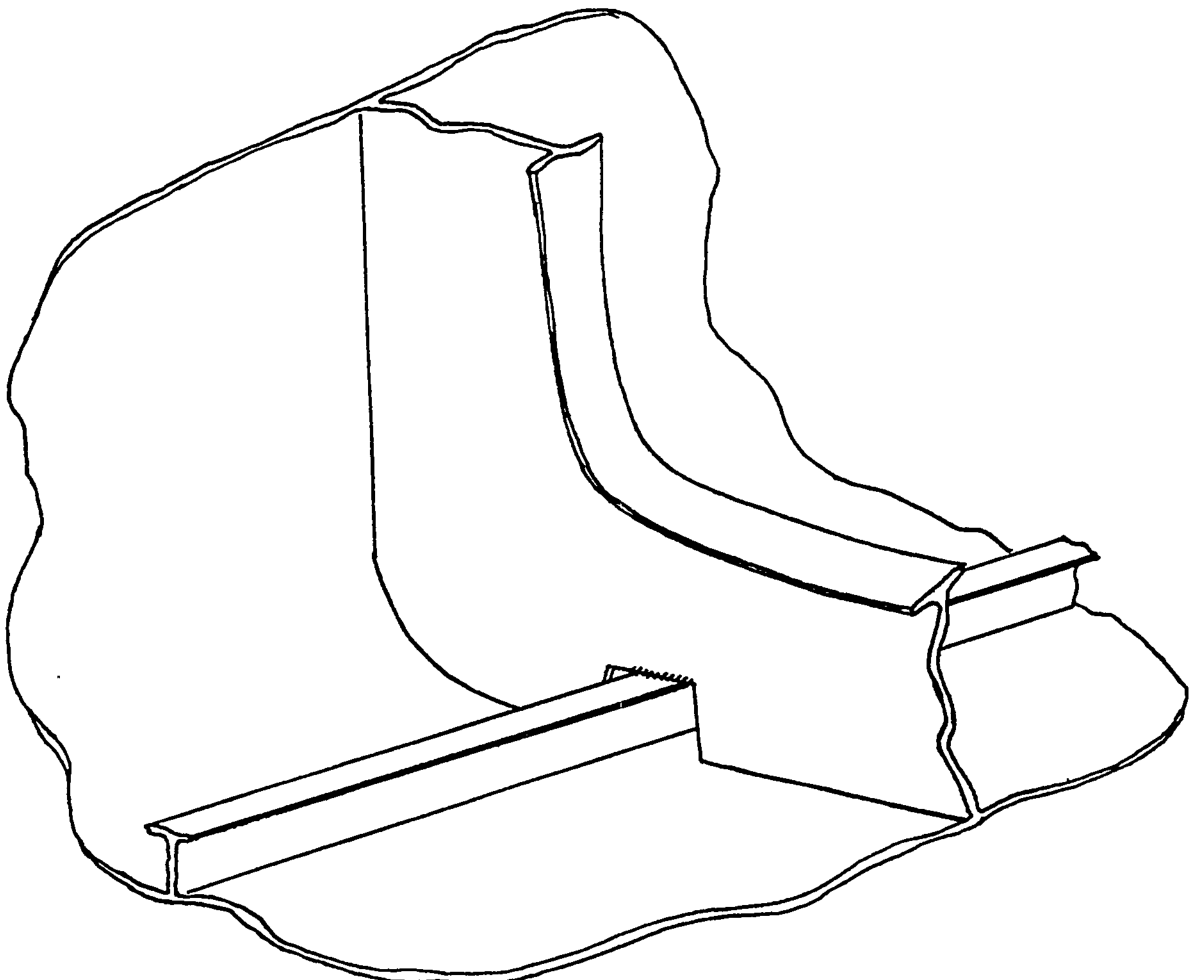


FIGURE VIII. B.2d

ALTERNATE TECHNIQUE IV.



NO EXTRA PARTS IMPLIES COLLARS DO NOT HAVE A LARGE ROLE .

FIGURE VIII. B.2e

ALTERNATE TECHNIQUE V.

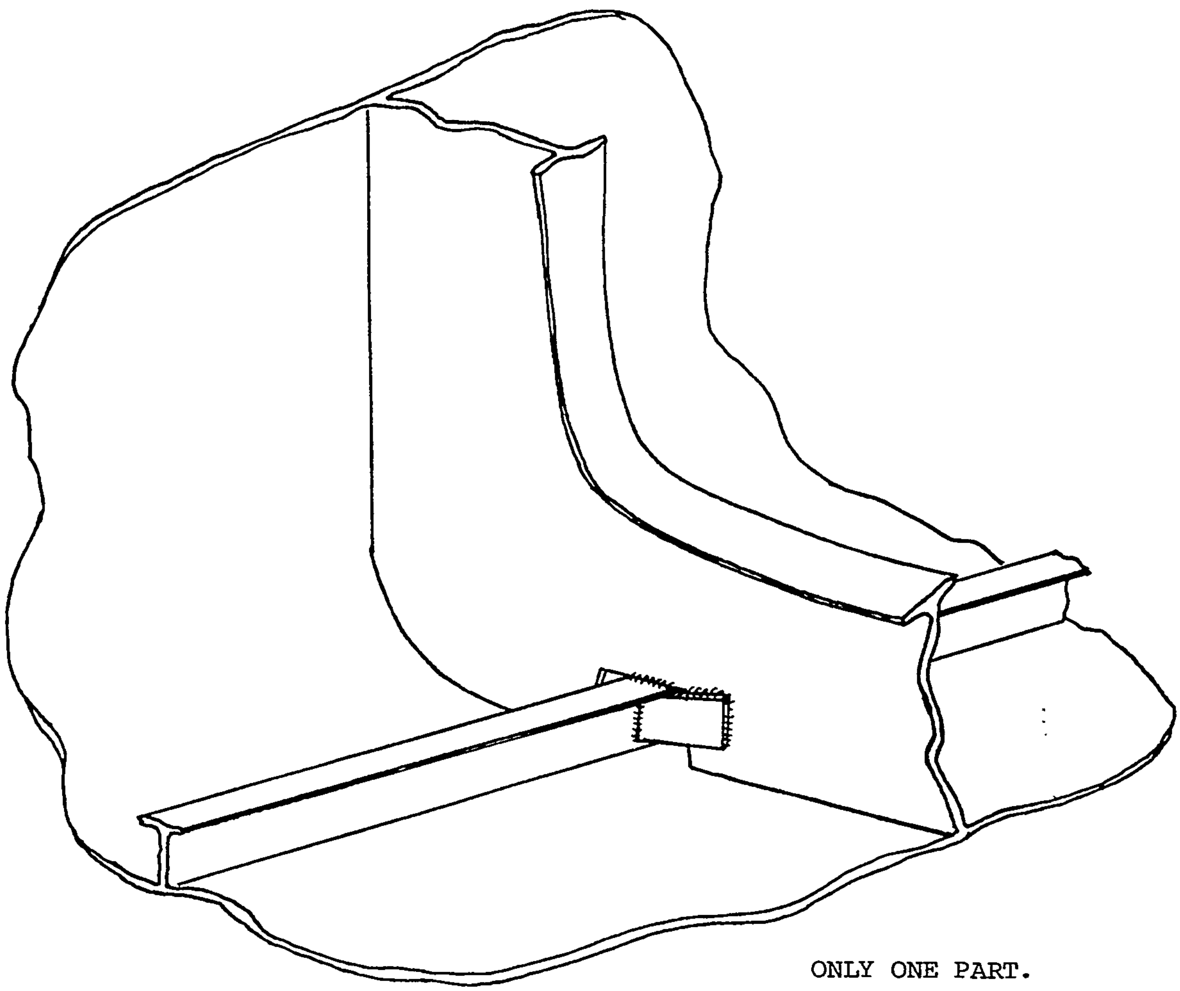
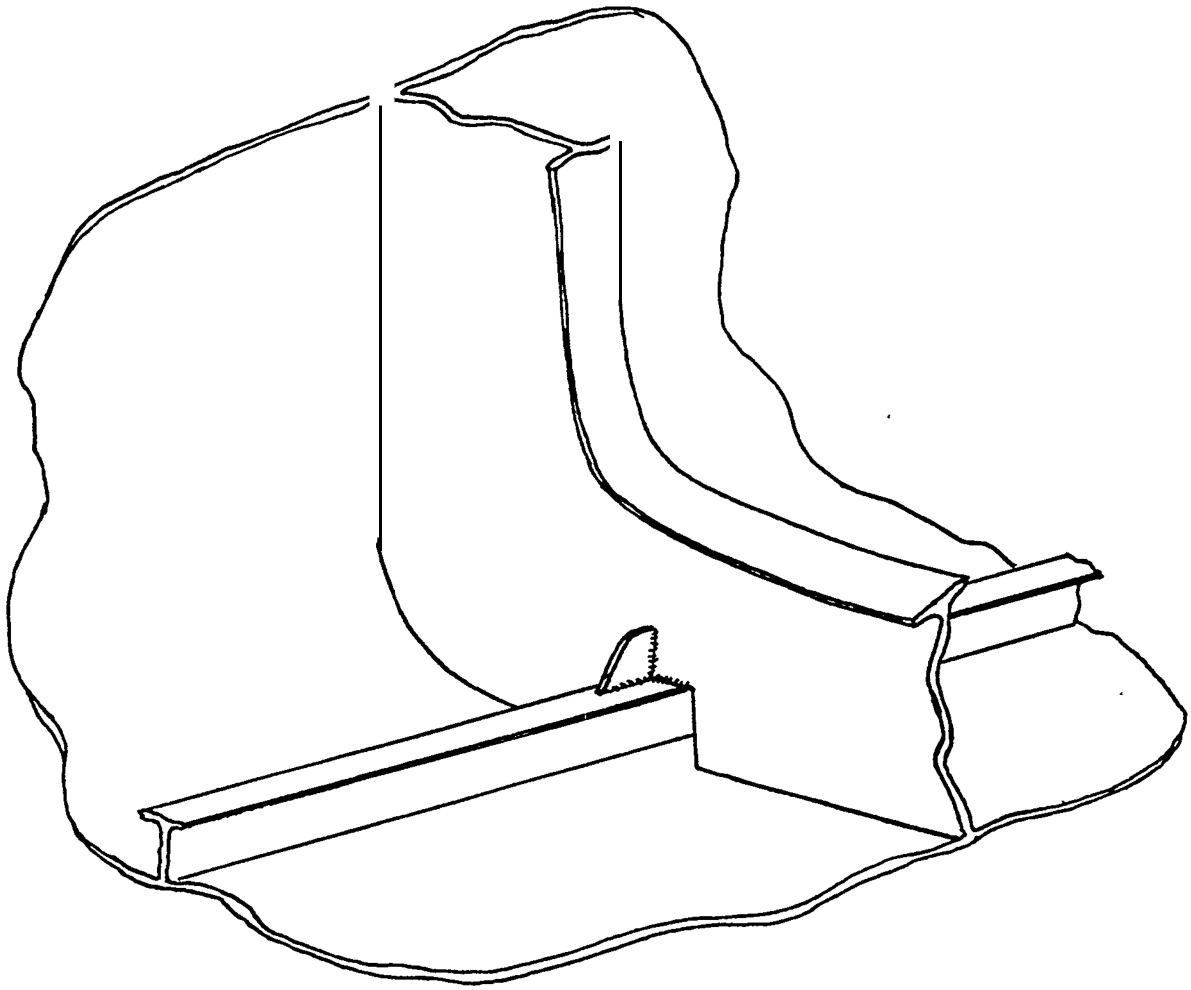


FIGURE VIII. B.2f

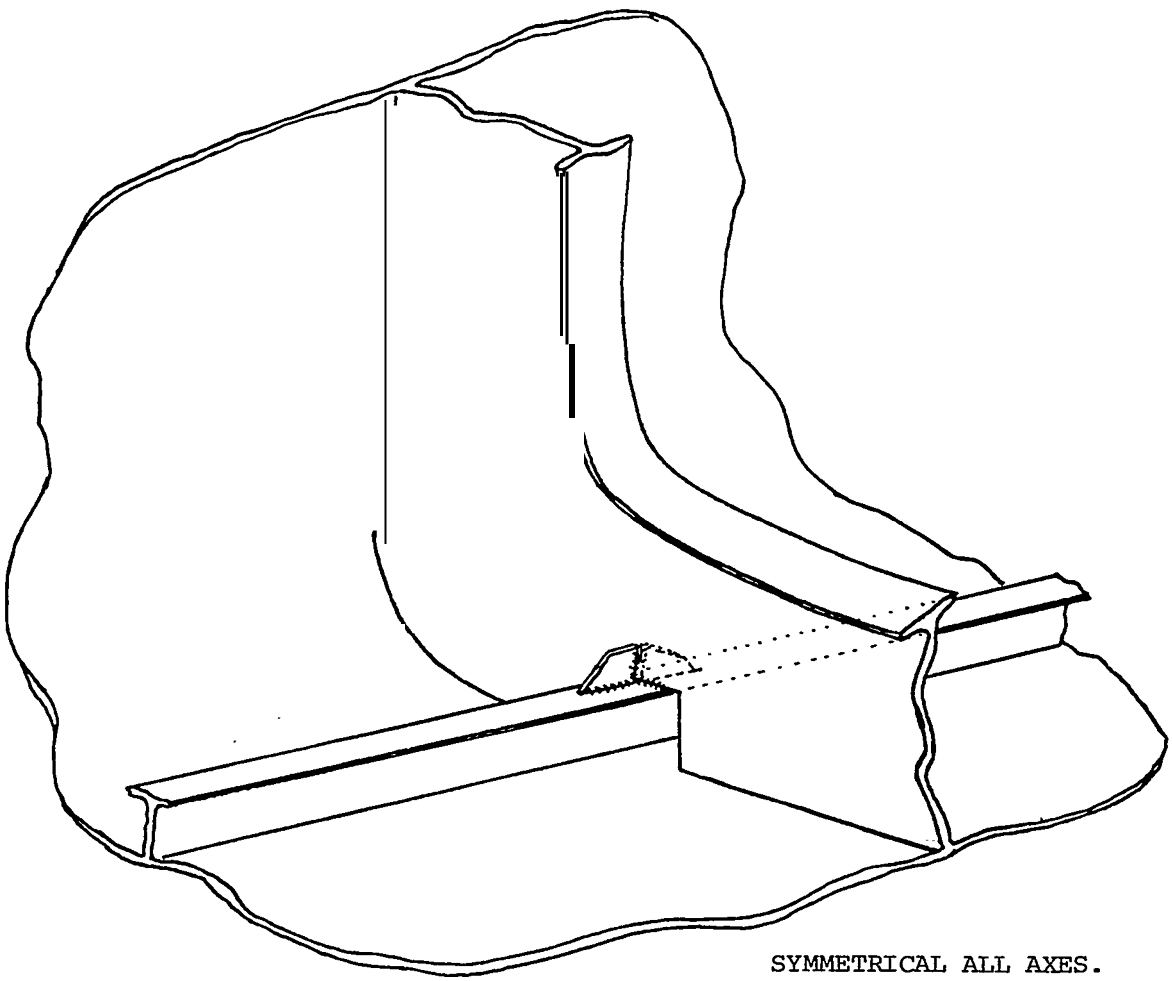
ALTERNATE TECHNIQUE VI



SYMMETRICAL (WRT LONG 'L)
ONLY ONE PART .
VERY ACCESSIBLE .

FIGURE VIII . B. 2g

ALTERNATE TECHNIQUE VII.



SYMMETRICAL ALL AXES.
ONLY ONE PART.
VERY ACCESSIBLE .

FIGURE VIII. B.2h

ALTERNATE TECHNIQUE VIII .

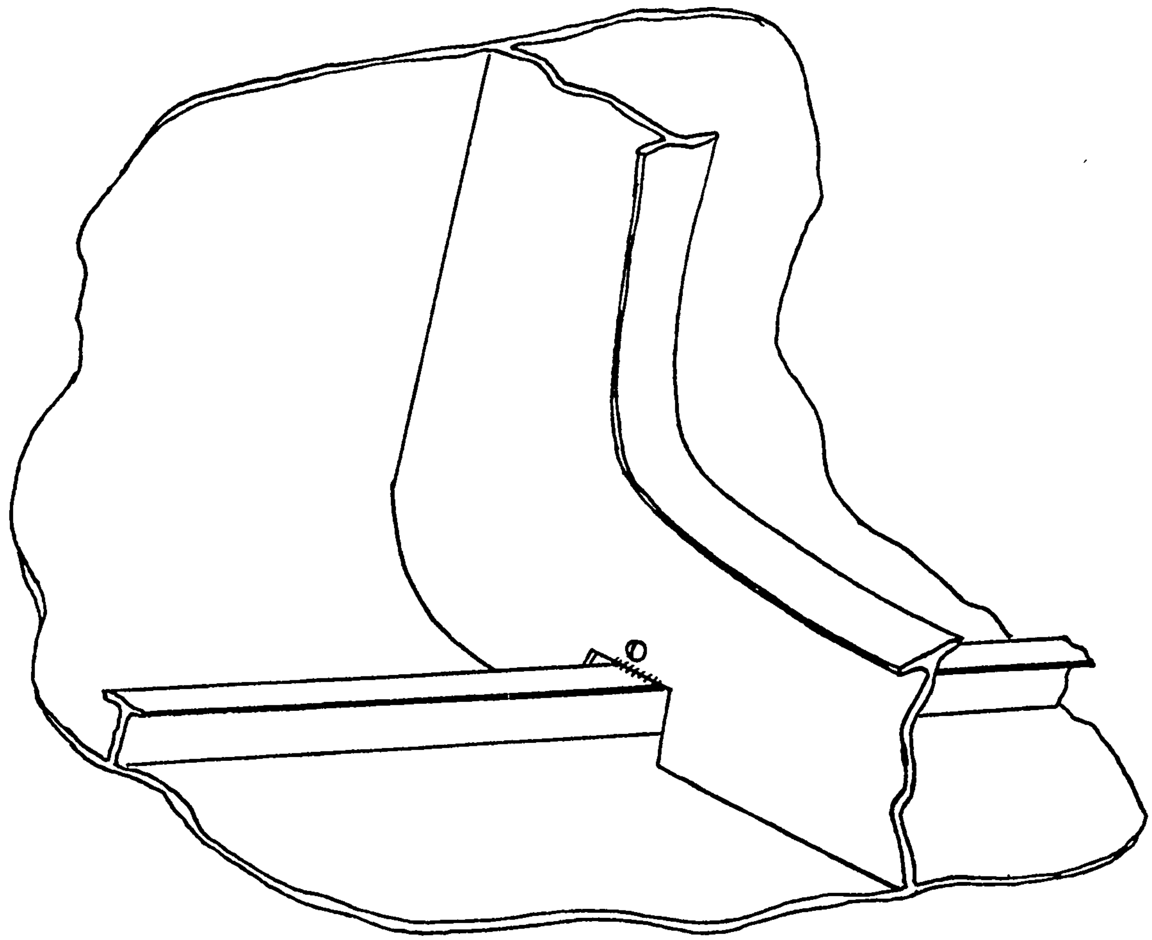


FIGURE VIII. B.2i

Notwithstanding, the recommendation is to first address the parts count issue by using design and analysis and information-transmission techniques to reduce parts-count and simplify structural details, and only then to consider what forms of erection automation may be useful.

Figures VIII. B.2a through B.2i are a portfolio of sketches of practice and ideas concerning structural details. Comments regarding individual sketches include the following:

a. This depicts common practice. These collars make fine tripping brackets but their functions in replacing shear web in the frame or to unload web-to-web forces are very dependent on their size and how they fill the frame gap.

b. This design, not recommended, serves only as a tripping bracket and loads the plate in doing so.

c. This design, recommended for certain applications, uses no small parts. It serves to unload web-to-web forces and as a tripping bracket. With addition of a single collar, it could also serve to replace frame web lost. Functions are enhanced by small clearances.

d. This design, not recommended for application close to a frame, serves only as a tripping bracket, loading the plate.

e. This design is recommended wherever only a tripping bracket is needed at a frame.

f. This design functions as that of sketch c at the cost of a single part and is recommended only if the design of sketch C is indicated but cannot be implemented.

g. This design uses a single part and fulfills collar functions except for replacement of shear-loaded frame-web material.

h. This design serves as the design of g. The added cost and complication gives symmetrical loading.

i. This design serves as tripping bracket and unloads the frame-to-longitudinal web-to-web forces. In this second function, the unloading involves a softening of the area to web-to-web forces rather than a stiffening of the area as provided by other designs.

c) Non-hydrostatic Loads

The matter of non-hydrostatic loads on a ship’s structure is similar to the question of wave loading in that uncertainties or overly conservative standards lead to overweight ships. The mechanism is a bit different for the typical set of loads; tug loads, drydock and shoring loads, wharf and pier loads, &c. The non-hydrodynamic loads impose constraints on shell or plate thickness and perhaps some frame and longitudinal placement constraints, thus absorbing much of the design freedom a structural designer may otherwise have. It is not obvious that better knowledge of these loads would give the designer some of his freedom back; it may be worth while finding out.

d) Heating Distortions

One knowledge issue which can have impact on productivity is the issue involving heating due to welding or line-heating, residual stresses, dimensions and distortion, order of part presentation and welding, and their interactions. Clearly substantial work has been done on line-heating to the point that it's accepted technique for generating shape and dimension changes. It occurs to us that the inverse problem, that of contriving dimensions, order of part presentation, and order of weld-bead generation, or order to yield finished products of predicted proper size and shape, is one that has the potential of increases in productivity subsequent to its resolution. The issue in this regard is rework and the ability to cut structural parts once without leaving extra stock and without trimming to size at any of several subsequent steps. There are many components to the error that extra stock compensates for, including measurement and layout error, cutting equipment that is out of shape and calibration, as well as distortions due to the heat cycles that the parts in question experience. This last component may be dominant and it is not amenable to simple accuracy-control techniques. Heat distortion is known to be a function of material, temperature distribution, and residual stress distribution. It is thus somewhat predictable or deterministic. If some extensive effort can codify heat distortion prediction so that it can be readily used as a plate-design tool and a planning and construction tool, then yards can more fully realize the potential of accuracy control and possibly a significant reduction in structural-member recutting and in yard measurements to match and mate adjacent structural entities.

2. Design Issues

a) Structural Tradeoffs

Amongst design issues are a set of considered structural configurational changes that have a potentially large favorable impact on construction costs but come with unfavorable impacts on other aspects, such as structural weight. Examples are the use of bulb-flat ("ell"or angle) longitudinals, simplified structures with fewer frames and longitudinals, and the Nappi, Walz, and Wiernicki "No Frame" Concept. (3) The trade-offs involved with any of these examples are usually easily calculated and some of the candidate changes have been shown to be useful for certain ships and not for others. We have no particular brief for any one of them but maintain that such simplifications should be considered for each design. We also note that in the case of weight-sensitive surface combatants such as cruisers, shell-thickness requirements to satisfy non-hydrodynamic loads seem to also determine an upper limit on structure complexity and a lower limit on structural weight through the relationship between shell thickness, compressional loading, and stiffener spacing. It appears to us that a ships' structural designer has really very little freedom in the preliminary design of a cruiser-sized ship where performance and speed are issues. It is with ships where weight, thus performance and speed, are negotiable, that a structural designer can simplify a ship's structure.

There are things that the detail designer and the planners can do, given the ship's scantlings, that can make significant differences in cost of manufacturing and erecting ships' structure, and we have seen such details for improving manufacturing and erection codified into instructions which pass from yard to detail designers. Details include such things as the structural junctions between topsides, decks, and beam stiffeners, length and straightness of welding runs, and so forth. There are opportunities for material-handling and welding automation in the erection of smaller structural subassemblies for ships. A good example is given by the Avondale - R.A. Price proposal(4) for a Semi-Automatic Web-Line (December 1984), which addresses stiffener-beam and web transport, relative placement, surface preparation (blasting to remove primer) and welding of beams to web, for flat webs. Extension of the technology to similar but not-flat plate and similar but curved and twisted beams is technically feasible. Economic feasibility of course depends on many variables, not the least of which is the detail design of the ship's structure. Clearly, capital costs are related to the degree of sensing and automation sophistication required for a spectrum of tasks, and the task spectrum is determined by detail design and by planning of assembly sequences. One of the keys to automating beam-handling and welding in such a system is the establishment and maintenance of known location for the web or plate.

b) Automation of Design

The issue of automating various ship's design processes is one where there remain many opportunities but where a great deal is already available and accomplished. In the area of structural design, the usual aids are available and in use at the preliminary design level. These include C.A.D. systems for design geometry, analysis programs (C.A.E.) for a limited set of structural calculations, and spread-sheet programs that have been adapted for rapid exploration of design trade-offs where relations have been established. Opportunities remain where computer design aids are limited by the combination of what is commercially available and the unique needs and requirements for ship design. The limitations generally are associated with the fact that ships, and ship drawings, are very complicated things. Ship drawings are extensive and carry written and pictorial information beyond the capacity of C.A.D. C.R.T'S, for example. Ship's structure is complicated such that the usual structural analysis software is limited to gross analyses which completely ignore the detail of ship's structure or to local analyses of small segments of structure to verify the stresses of any of many different structural details of a ship's structure. A consequence of this complication is the fact that manual and standard structural design methods still have a significant role in ship's structural design. In the matter of structural design, it is our opinion that very little if any would be gained from the availability and use of much more extensively detailed (many more nodes) structural analysis computation.

3. Construction Issues

When automation is considered, one generally thinks of automation in manufacture and assembly rather than in design or planning, and there do exist opportunities for automation in the manufacture and construction of ship's structure. There are tasks that are technically feasible to automate, but economic feasibility generally depends on many variables, many, perhaps most, of which are beyond yard control. Typically, moves toward automation imply increases in the ratio of capital to labor cost.

An increase in capital to labor cost rates requires a modicum of stability in work load, both type and quantity of work, for justification, most especially so in industries where labor turnover is high. AS automation proceeds in an industry, payback periods for capital investment generally increase as more and more marginal and more difficult tasks are addressed. Clearly investment is increasingly shaky as payback periods climb to match or exceed the time extent of the order book. While we are experienced in the quantification of such arguments, we do not yet have the data to do so for the shipbuilding industry, so that comments here are largely limited to technical feasibility. The basis for economic feasibility calculations are both yard- and shipbuilding program-specific.

a) Stock preparation

Structure raw material consists of rolled steel shapes, mostly “I” beams, of various sections and sizes, and rolled steel plate of various thicknesses and one, two, three, or more different materials. Occasionally raw material may also include aluminum plates and rolled shapes, and steel-aluminum composite joint plates. It occurs to us that it is technically feasible to automate every, or virtually every process in transforming raw stock into primitive structural elements prior to the first welding pass, if no bending or shaping of beam or plate is required; and, that some beam or plate bending or shaping is also feasible to automate.

Tasks encompassed in this aspect include:

A. Recovering stock from structured storage.
B. Connecting oriented and located raw stock elements into a process-lane conveyor or transport means.
C. Blasting stock or cut parts to clean.
D. Priming or painting stock or cut parts after blasting.
E. Flame-cut, saw-cut, or plasma-cut shapes, beams, or plate-
    1. Cut to alter shape; example, “I” beam to “T.”
    2. Cut shape to length.

3. Cut shape to shape.

4. Cut plate to plate parts.

F. Mark to facilitate later bending or installation.

G. Apply bar-code or other I.D. for later use.

H. Remove paint locally, along lines for subsequent welding.

I. Convey stock through process lane, maintaining location and orientation knowledge, from raw stock stage to completion of task set.

Each of the elements of a system to accomplish these tasks has either been implemented or has been proposed at one or another shipyard. A serious proposal for a system to accomplish a limited but expandable combination of the above tasks is being implemented in a form more limited than the proposal. However, we are not aware of any yard proposing or implementing a system to accomplish all of the above tasks.

A note of caution is in order here. Implementation of a complete system of the sort suggested here may represent both a great economic success in the short-term and an awkward or embarrassing handcuff a decade or more in the future. With a payback-period of, say, three years, one may claim this is no issue. Notwithstanding, there exists an active producing yard today which is limited in its ability to do extensive pre-outfitting of structural blocks. It continues to use construction facilities specialized to handling very large structural blocks by techniques which were economically advanced when the yard was conceived and built in circa 1970. The fact that the capital investment implicit in the yard's facility was likely to have been fully amortized a decade ago has apparently been insufficient spur to further upgrade facilities. In any case, substantial capital investments in economically justified systems that enforce a sequence or procedure do reduce flexibility.

The other operations which may be involved in preparing raw stock for welding into structure include bending and twisting of structural shapes and imposing simple and compound curvature upon plate parts. The first three tasks are typically press work and automation is technically feasible. The last task may involve press work but typically involves line or spot heating. Automation may or may not be technically feasible; at best, residual stresses are a major unknown and uncontrolled variable which impose large uncertainties on the outcome of line-heating. It is only under conditions of huge plastic deformations that press-work can be confidently done open-loop, and the plastic deformations associated with shipbuilding press work are typically quite small. Thus successful automation of beam-shaping and developable bending in shipbuilding will involve sensing and an algorithm for task-monitoring which depends on measurements.

To some extent we have the benefit of hindsight in this assertion. An attempt to automate the bending of longitudinals and similar "T" beams in an open-loop fashion has been plagued with uncertainties in final curvature which possibly can be traced to uncertainties in material properties such as yield strength, temperature, state of residual stress, initial curvatures and so forth. Attempts to accurately impose new shape, by means of small plastic deformations, on an uncertain ductile material, is typically an iterative task as well as one requiring sensing; it is iterative in that plastic deformations are imposed only via the press deforming the subject through the elastic region, while sensing or verification of the new shape is done only under **circumstances of no external load.**

Thus we suggest that virtually all processes involved in transforming the raw materials of ships' structure to readiness for welding are technically feasible for automation; but that economic feasibility is dependent on various factors, many of which are beyond yard control.

b) Welding

A great deal of attention has been paid to welding automation in shipyards and various forms of welding automation are already in use. We have seen rod-fed simple gravity welders in use in egg-crate structure, wire-fed beam followers that ride longitudinals and weld long beads on both sides of the longitudinal at the meeting with the late, and a wire-fed robot-borne welder working on welding of small structural parts. Much welding automation is well-established and mature technology. Certain welding automation technologies are suitable for a narrow range of tasks and unsuited to tasks outside the range. Rod-fed gravity welders, for example, are quite suited to welding structural egg-crates where straight runs are short; the rod is only capable of a short bead. Additionally, we understand, gravity welders are not adaptable to H.-Y. or H.-S. steels. The established technologies are well-known in terms of their applications, costs, and productivity, and their applicability covers much of structural welding, especially of commercial ships or of mild steel.

There is good potential for productivity improvement to be gained from systematically automating welding processes. Such automation should begin with planning of heats, wire sizes, metal deposition and welder travel rates, and sequences of welds on workpieces. The goal is to combine measurement, planning, and weld system programming to create low distortion welds. It is hoped that the ability of an automated system to obey the planned sequence and repeat it uniformly will yield parts of repeaitable distortion, possibly low distortion.

It is important to point out the difference between this kind of project and the typical welding project. The latter tends to focus on the welds themselves, whereas the latter means to integrate welding, measuring, and planning into a system that creates finished products that meet a certain specification.

There is room for extension of welding automation technologies for ship building into other realms, but as usual, what is possible technically may not be economic. Three extensions foreseen as perhaps of use include: the handling of backing material or a transient backing automaton for one-sided welding; automation of welding techniques for materials that require preheating or temperature control; and hardware and software to implement seam-following without beam-following. It would appear that automation of the backing function or of preheating would require mobile robotics or a manipulator mounted in a large robotic Cartesian gantry. versatility and dexterity over unusually large distances would be needed to implement any sort of cooperative routine between a robotic backing device and robotic one-sided welding. Even though manipulator-to-work forces may be small in welding and moderate in backing, deflections and rigidity may be the technical issue that limits scope and versatility of such implementations.

As earlier implied, when automation is developed step-by-step in a family of processes, the development often moves from the technically more simple to the more complex and from the economically most feasible to the most marginal. Currently the situations in ship-structure welding where automation is technically and economically feasible are limited; gravity-welders working in mild-steel egg-crates, and beam-following two-sided welding on long stretches, for examples. Since both technology and economics control development and application, changes in either can affect feasibility. Economic changes which favorably affect or extend feasibility or applicability of automation are lengthening of order book, reduction in interest rates and cost of money, cost of labor, and where safety or environment are an issue, costs of having human labor deployed. The striking reduction in cost of money as this is being written may be a spur that extends the spread of automated tasks or applications.

There are two other tasks associated with welding which are often performed subsequent to completion of the weld-bead and which are technically feasible to be automated. These tasks are the chipping, cleaning, and removal of flux and slag from the weld, and the dressing by grinding of the weld where smoothness is an issue - hull surfaces, stressed regions, edges where people contact the welded surface. While one can imagine a flux-cleaning automation that uses sensing to determine completion at a bead region, one can also imagine an automation with no sensing and very little sophistication that accomplishes its task by dwelling long enough in any region that no slag could survive the history of percussion. Since hammering on the bead and nearby parent metal has no ill affects and may have beneficial effects, such crude open-loop automation may be quite appropriate. Weld-bead grinding-to-finish is quite different in that damage is done if the tool dwells overly long and the job is not done if the dwell is insufficient. Additionally, wheel speed, tool forces, and tool-to-work attitude must be controlled. Automating weld-bead grinding-to-finish thus depends on various sensor-based and data-base information for control of the process. Work on the topic proceeds in various laboratories including our own and the elements of controlling tool-forces through sensing has been demonstrated in our laboratory.

c) Measurement

In our discussion on the question of automating manufacture of ships' structural parts prior to welding, an emphasis was placed on "structure" in the sense of knowledge of location and orientation of each piece. Such "structure" was presented as a sine qua non, an essential, to automation. In the matter of automating some of the tasks associated with assembly of structure, "structure" in the sense of locational and orientational knowledge is importantly useful and perhaps essential too; additionally, such "structure" may permit instrumentation and automation of another structure assembly function, that of measuring, knowing, and controlling the geometry of the growing structural block. While each of the subject tasks discussed as candidates for automation in structural assembly above could conceivably be implemented standing alone, some synergism is associated with integration of the tasks into a system that includes coordinate measurement of designated points and maintainance of structure location and orientation information. This dependence is outlined in Table VIII. B.2.

c. Summary

This section has partioned the structural automation problem into several parts. Major ship's structure is exquisitely designed, and suggested changes to improve producibility are likely to cause severe changes in highly important areas. Such

TABLE VIII. B.2.
THE USES OF LOCATIONAL AND ORIENTATIONAL
INFORMATION FOR THE AUTOMATION OF VARIOUS STRUCTURAL ASSEMBLY
TASKS

TASK ASSOCIATED WITH ASSEMBLY OF STRUCTURE:	KNOWLEDGE OF LOCATION AND ORIENTATION OF BASE STRUCTURAL ELEMENT AND SUBSEQUENT ELEMENTS PROVIDES:
LAYING WELD BEAD.	APPROXIMATE KNOWLEDGE OF LOCATION OF BUTT OR JUNCTION TO BE WELDED.
BACKING WELD BUTT.	SUFFICIENT KNOWLEDGE OF LOCATION OF THE BUTT TO BE BACKED AND WELDED.
BREAKING AND REMOVING FLUX SLAG FROM WELD BEAD.	SUFFICIENT KNOWLEDGE OF LOCATION OF WELD-LINE TO BE CLEANED.
GRINDING-TO-FINISH OF WELD-BEAD.	SUFFICIENT KNOWLEDGE OF WELD-BEAD LOCATION AND WORK ORIENT-ATION THAT THESE VARIABLES CAN BE DRAWN FROM DATA-BASE OR RELATIONS AND NEED NOT BE SENSED.
MEASUREMENT OF SELECT POINTS ON STRUCTURAL BLOCK, INCLUDING DESIGNATED POINTS ON TENTATIVE PLACEMENTS.	SIMPLE SEMI-AUTOMATED MEASURE-MENT ROUTINE FOR POINTS ON GROWING STRUCTURE. OPTICAL AND OTHER MEASUREMENT TECHNIQUES RELYING ON STATIONS FIXED IN THE WORK SPACE AND WORK-BASE FIXED AND KNOWN WITHIN THE WORK SPACE. GROWTH AND EXTENSION OF KNOWLEDGE OF STRUCTURE GEOMETRY AS STRUCTURE GROWS.

changes therefore should not be made for the sake of producibility unless several apparent knowledge gaps in ship structural design are filled.

we are then left with several other automation or design issues. Minor structure, especially structural details, present many hand operations that are difficult to automate. Redesign, based on improved understanding or improved statement of function, should be pursued before automation is considered.

Automation or standardization of some aspects of Stuctural design will improve producibility as well as the efficiency of the design process. Knowledge gaps exist in predicting stress levels, heat-induced distortion, and tolerance buildup.

A suitable culmination of better knowledge would be welding or cutting systems that combine astute choices of weld or cut sequence, direction, speed, and heat input to maximize accuracy.

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3. “The 'No-Frame' Concept-Its Impact on Shipyard Cost,” N. Nappi, R. Waltz, C. Wiernicki, Naval Engineers Journal, May, 1984, pp 218-232.

4. “Semi-Automatic Web-Line Feasibility Study,” Maritime Administration-Avondale Shipyards, Inc., December 1984.

IX. FLEXIBLE AUTOMATION POTENTIAL IN SHEET METIAL

A. Introduction

This section discusses the potential for and blockages to automation in shipyard sheet metal work. The focus will be on ventilation duct because it is so dominated by built-to-order items. Other sheet metal products (sinks, lockers, furniture) are either too few and specialized or are standard purchase items. On long-term multi-ship programs, the Navy could make quantity buys from one vendor or yard for items like lockers or water tight and metal joiner doors.

Ventilation remains the major target for shipyard automation. The next subsections describe its design and fabrication, plus recommended automation options.

B. Current Status of Design and Fabrication

Ventilation is a vital life-support system on ships. on DDG-51 and on later members of the CG-47 class ships, the vent system must provide Nuclear-Biological-chemical (NBC) defense. This adds active dampers, pressure sensors, and controllers, and makes ventilation into a complex control system. This characteristic contrasts strongly with previous vent systems, whose design was based on steady delivery requirements, few sensors and moving parts, and slow reaction times. Therefore, building, installing, and testing such systems will be more complex and costly than in the past.

Both conventional and NBC vent systems must meet watertight compartmentalization and damage control requirements. Most vent below decks and some above must qualify as watertight (WT) which means that it must not leak, burst, or collapse when subjected to positive or negative heads equivalent to deck-to-keel heights. This works out to 15 to 20 psi. Vent systems must remain within designated damage control regions of the ship. Supply and exhaust fan rooms, usually located above decks, must be separated from each other and must feed or exhaust many distant compartments.

Since communication, command, and control (C^3) have first priority on above decks space, fan rooms are small and consequently are crowded.

Although not all vent must meet WT requirements, some vent must be drip-proof (DP), meaning that water which collects inside must not leak through and drip on water-sensitive equipment. In addition, vent must be strong enough to survive shock from combat as well as everyday contact with sailors. Tail ends of vent delivery systems within compartments often can be non-water tight (NWT).

Even conventional vent systems are complex to design. Before exact vent routes are known, the pressure drops and required flows must be estimated or calculated so that fan rooms can be sized and required equipment can be identified. Very serious consequences result from the discovery that a fan room is too small, athough this occasionally happens.

In the case of Navy ships, NAVSEA, as part of contract design, allocates fan rooms to the compartments they serve, calculates required delivery of air in terms of CFM and temperature, and both sizes and lays out equipment in fan rooms. Although the allocations obey the damage control boundaries, no detailed routing or sizing of vents is done at this stage. The Design Criteria Manual summarizes the contract design for vent.

The detail designers must do the following:

1. Recheck the calculations made by the contract designers.
2. Plan the sizes and routes of all vent ducts.
3. Determine shapes or coatings to control noise.
4. Calculate pressure drops and determine if the fanrooms or their equipment are sufficient.
5. Determine sizes, shapes and some of the fabrication requirements for individual duct pieces.

6. Make equipment lists.

Yard or shop designers determine material type and thickness, construction method, and joint types. Most of the power over producibility is thus in the hands of detail and yard designers.

Guidance for designers is provided by the ship specification. There are no MIL-SPEC'S or MIL-STD’S for vent that we could locate. The ship spec, Section 512, provides some general guidance such as:

round duct is preferred over rectangular
rectangular, where used, shall have aspect ratio less than 3.5:1
vent routes shall be straight where possible
abrupt changes in size or shape should be avoided
welded construction is preferred for WT duct

These are often honored more in the breach, since, for example, nearly all vent is rectangular because of space considerations. The size of vent and shortage of overhead space make routing difficult. Especially in fan rooms, quite odd vent contortions and size/shape changes occur every foot or two. An example is shown in Figure IX.1.

Specific standards are given regarding material thickness. Portions of these requirements are shown in Table IX.1. Minimum thicknesses are given for aluminum and galvanized steel for both WT and NWT applications. Joining methods are also restricted. Crimped joints within a piece of duct are not allowed in WT or DP duct. Welded joints are required, and we saw only arc (usuallY TIG) being used. Duct pieces can be joined by flanges with gaskets on any type vent and by heat shrink tape on round NWT joints. WT vent usually has surprisingly heavy flanges made of angle iron or welded-up structure.

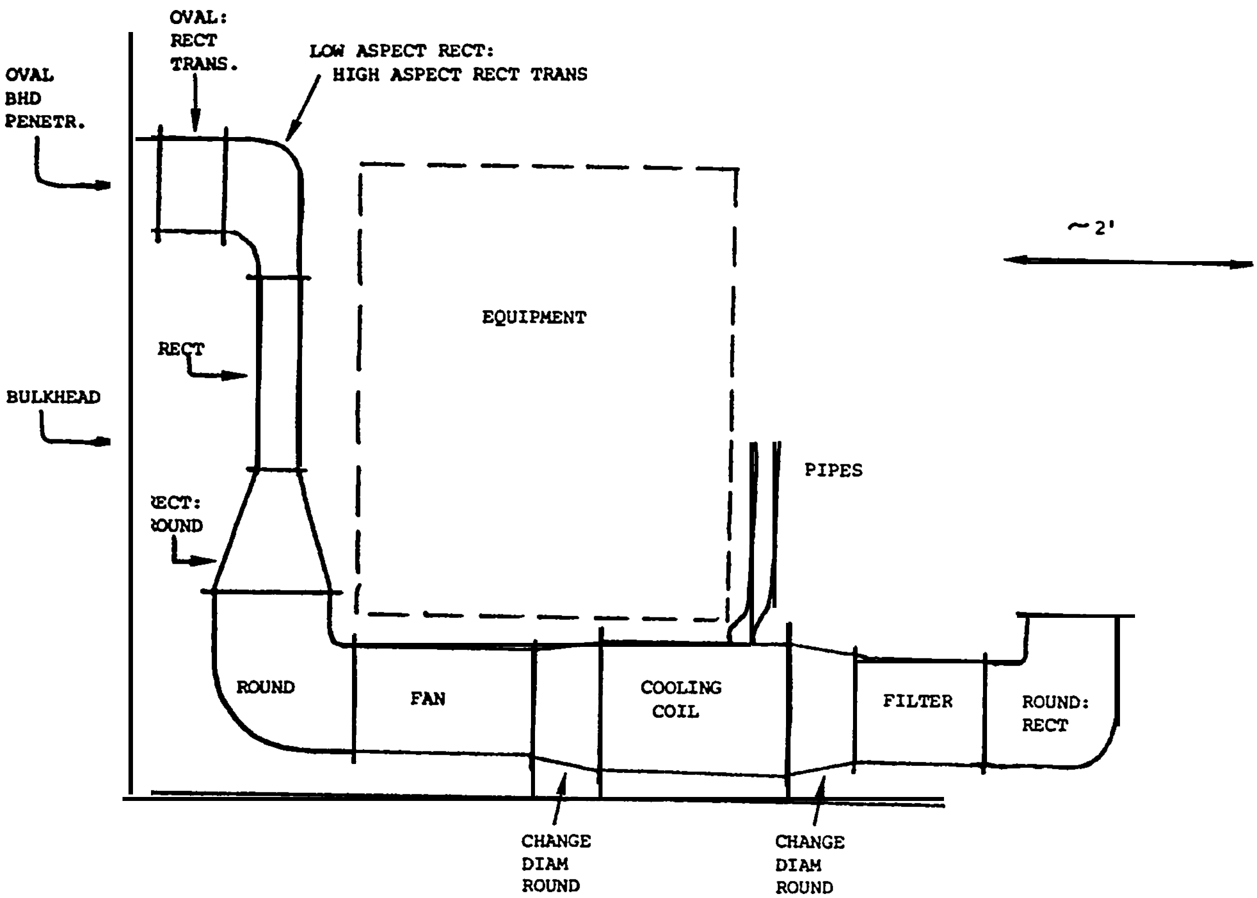


Figure IX. 1: Typical Vent Design in Crowded Fan Room

	NWT		WT	
DIAMETER	GALVO	ALUMINUM	GALVO	ALUMINUM
less than 6"	0.018"	0.025	0.075	0.106
6.5 to 12	0.03	0.04	0.10	0.14
over 30	0.06	0.08	0.118	0.16

SPIRAL WOUND DUCT

DIAMETER	GALVO	ALUMINUM
less than 8"	0.018"	0.025
Over 8	0.03	0.032

TABLE IX - 1

Minimum Wall Thicknesses vs size for some Navy Ductwork, based on Section 512 of Gen Specs.

Designers therefore face a number of problems in vent duct design:

1. Deciding the routes
2. Coexisting with structure, equipment, pipe and wireways.
3. Maintaining required flow and pressure.
4. Controlling weight.

In response to these requirements, designers have brought the following tools to bear:

1. CAD systems that calculate pressures and flows .
2. CAD systems for laying out vent routes.
3. Both 3D CAD and 2D computer or manual overlay techniques for detecting interferences and seeking routes in the presence of other distributive systems.
4. CAD systems for creating sheet metal developments or other flat piece layouts that can be bent or joined to form various classical types of vent shapes.
5. Computer-driven plasma cutters that cut out these sheet metal shapes to very good accuracy.

An interesting feature of the vent results from using this array of tools;, vent is a sequence of little segments, often only a foot or two in length. Each of these segments does a little job, such as converting one radius or shape to another, or turning a corner. The CAD system in use at one yard encouraged this by forcing the designer to define the vent one such little piece at a time. The route therefore emerged implicitly. By contrast, the same vendor’s software for pipe design allowed the designer to set the route first, then establish bends, fittings, and other parts of the whole. This would appear to be preferable, since it forces the designer to see the whole and break it down more efficiently into fewer pieces.

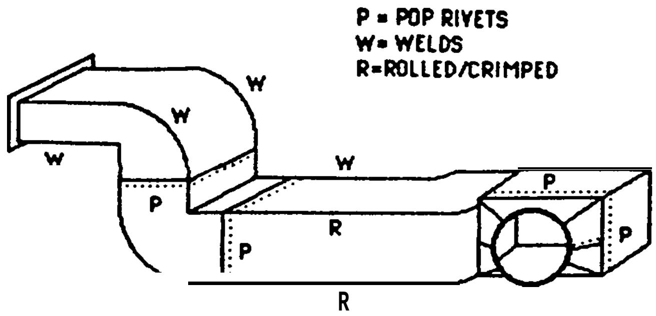
C. Comments on Vent Design and Fabrication

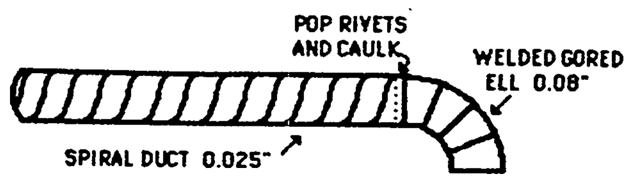
The individual vent segments are indeed ingenious, and are made feasible by the accuracy of NC cutting. But virtually all the remaining work is manual: bending, fitting, and welding. It is difficult to see how these manual steps could be easily automated given the philosophy of design that has created them.

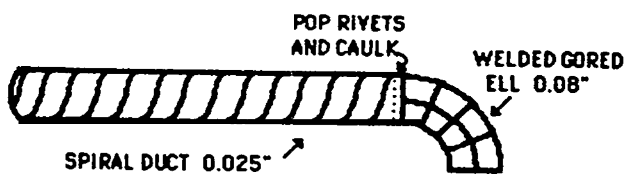
This philosophy and the supporting software encourage a large number of small segments which themselves are built up from several pieces. Some extreme examples of this philosophy are shown in Figure IX.2. It really is unnecessary to design some of these items this way in view of the fact that they are neither WT nor DP. Other examples in the figure are notable for the number of different materials and joining methods used. (It is worth noting that joint and material choices are not typically made by NAVSEA or a detail design agent such as Gibbs and Cox. These choices are made by shop planners at the yard. This is therefore an example of the freedom yards have to affect productivity by determining similarity of jobs, methods, and materials.)

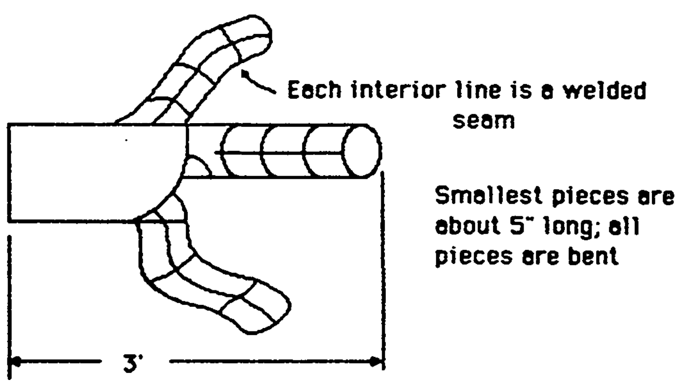
In response to the ingenuity of design, the varieties of materials and joint methods, and the contorted shapes of vent pieces, yards have developed a largely manual fabrication process. The first step is automatic, in which a plasma cutter cuts out shapes from steel or aluminum sheet, using hand loaded NC tapes or direct data links to design computers. This one automated step made an enormous increase in productivity. Cuts are fast, edges are clean and not distorted, cuts are accurate so that the pieces will fit, and thousands of templates are no longer needed.

With the exception of straight seam welds on rectangular ducts, the rest of the vent fabrication process is manual. Bends or creases are made in flat pieces by holding the pieces manually









A Complex Built-up Vent Assembly

Figure IX. **2:** Several Vent Pieces that seem poorly Designed.
All are fair representations of actual pieces seen in yards.

in hand operated or powered press breaks. The bent pieces are then joined, usually by two people at a workbench. One holds the pieces while the other welds them. One person can do it alone if the duct is small. Often there is little documentation other than a print showing the entire vent system. (For example, Figure IX.1 would serve both for fabrication and installation.) Overall, this is a lengthy process that often produces beautifully built, complex, awkward, and sometimes poorly designed pieces.

D. Possible Alternate Techniques

What are some alternatives? How do different yards respond to these problems? Since only a few ducts are DP, let us focus on WT and NWT.

Crimped construction is permitted on NWT. Some yards have embraced this opportunity in several ways. They make heavy use of spirally wound duct. One may buy such duct or, as one yard did, buy a machine that makes it from reels of sheet strip. Figure IX.3 shows a typical machine. Such machines typically cost $75,000 to $150,000. Appendix 1 contains sample product literature. purchasing the machine solves many inventory and ordering problems.

One may also buy simple machines that form straight crimps for long straight duct or hand crimpers for short curved joints. Figure IX.4 is a sketch of some commercial vent made this way.

Some recent developments offer hope for improvement. Most significant is an ongoing study by the Life Support section of NAVSEA, conducted by Fred Saavedra. The aim of the study is to see if spirally wound duct could be qualified for WT use. The spur is to reduce the weight of ducts on ships, which can be as much as 50 tons on a destroyer. Aluminum duct is not desirable due to its vulnerability to fire, so the study is focusing on galvanized steel.

No conclusions or recommendations have been issued yet but several 8 inch diameter triple-ribbed ducts only 0.01" thick withstood about 64 psi without leaking or bursting. The duct showed

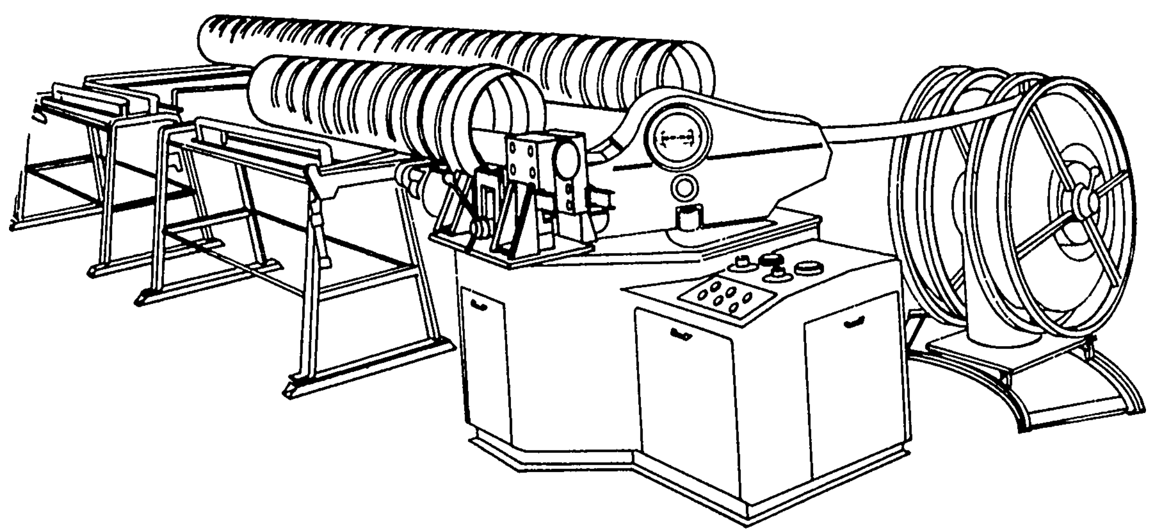
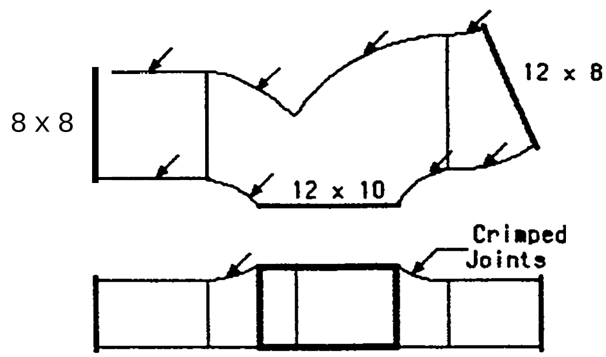


Figure IX.3: Commercial Spiral Duct Winding Machine



Example of commercial vent w th out-of-plane
crimped or rolled joints

good compressive strength as well. Since the existing spec can be met at about 15 to 20 psi, these results are promising.

Longer term, Mr. Saavedra wants to reduce the weight of components like fans and cooling coils, too, as well as to make them easier to repair. He is sensitive to the tightness problem in fan rooms as well as the need for designers to standardize on duct sizes. Finally, he hopes that use of spiral wound duct will simplify installation as well as fabrication of vent systems.

Of course, there are several caveats. Improperly designed or used duct winding machines can crack the metal in the crimped joints. Also one may wonder if the urge to make lighter duct is based on the questionable theory that “weight is cost,” discussed in Section XIII. The walls being tested are very thin, after all.

The most important caveat is that not all duct in a ship consists of straight runs. NAVSEA has not conducted any design studies comparable to the IHI pipe study on FFG's discussed in Section X. It may be that half or less of the running feet of vent are straight and without branches. Unless major changes in design philosophy and techniques are possible, the impact of spiral WT duct will be small in both weight and, especially, cost. This latter is due to the fact that straight duct is already fairly easy to make.

A possible cure for the unreliability of crimped seams is to replace them with continuous resistance weld seams. This is illustrated in Figure IX.5. The rollers create overlapping spot welds, making a gas - and water-tight joint. Roller clamping forces are typically 500 to 1000 pounds, and rollers can be as small as 2“ diameter. Figure IX.5 is from an advertisement by a vendor who says his rollers will work with galvanized stock and do not require external water sprays for cooling.

Another problem faced by advocates of round duct is that it takes up more space than rectangular duct. According to tables in commercial handbooks, the penalty is about 10% in both directions perpendicular to the air flow. (An 11” diameter round duct is equivalent to a 10” square duct, approximately.) A possible solution is to form round spiral duct and make it square or rect-

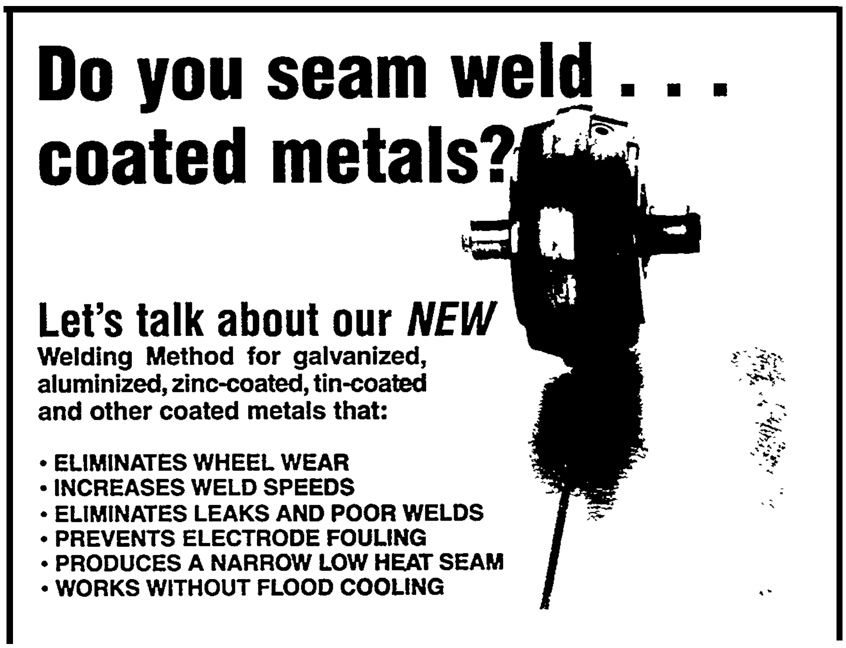


Figure IX. 5 : Example Continuous Seam Welding Equip.

Seam Welder from Soudronic, Inc.
465 North State Rd.
Briarcliff Manor, NY 10510
(914) 941-4808

angular later. Current commercially available methods for doing this involve placing mandrels inside the duct and forcing them out. This often damages the crimped seal. Less stressful methods are needed.

One yard shuns crimped construction entirely, regardless of WT or NWT. The reason given is that the sheet metal workers can concentrate on one fabrication process, welding, and do it well. One would think that this would require heavier wall thicknesses and longer joining times, but this yard was content with its choice.

The reason for discussing different design and construction philosophies is to point out two things:

a) Current design methods severely limit automation potential beyond cutting out the pieces.
b) Different design methods, based on different initial part shapes, joint locations, and joining methods, can lead to quite different and more promising automation potential.

As a small example, consider the five ways of making a gored elbow shown in Figure IX.6. Assuming the ell has 4 segments, one may design to have as few as one component part or as many as 8, as few as 3 welded seams or as many as 14. We have seen designs (c),(d) and (e) in use, but not the simpler (a) and (b).

E. Financial Data

Some limited data on sheet metal shop costs on a recent destroyer were made available to us. The data record man-hour charges by SWBS category. The following conclusions emerge from the data:

1. Major cost categories are:

Fabricate and install vent	**41%**

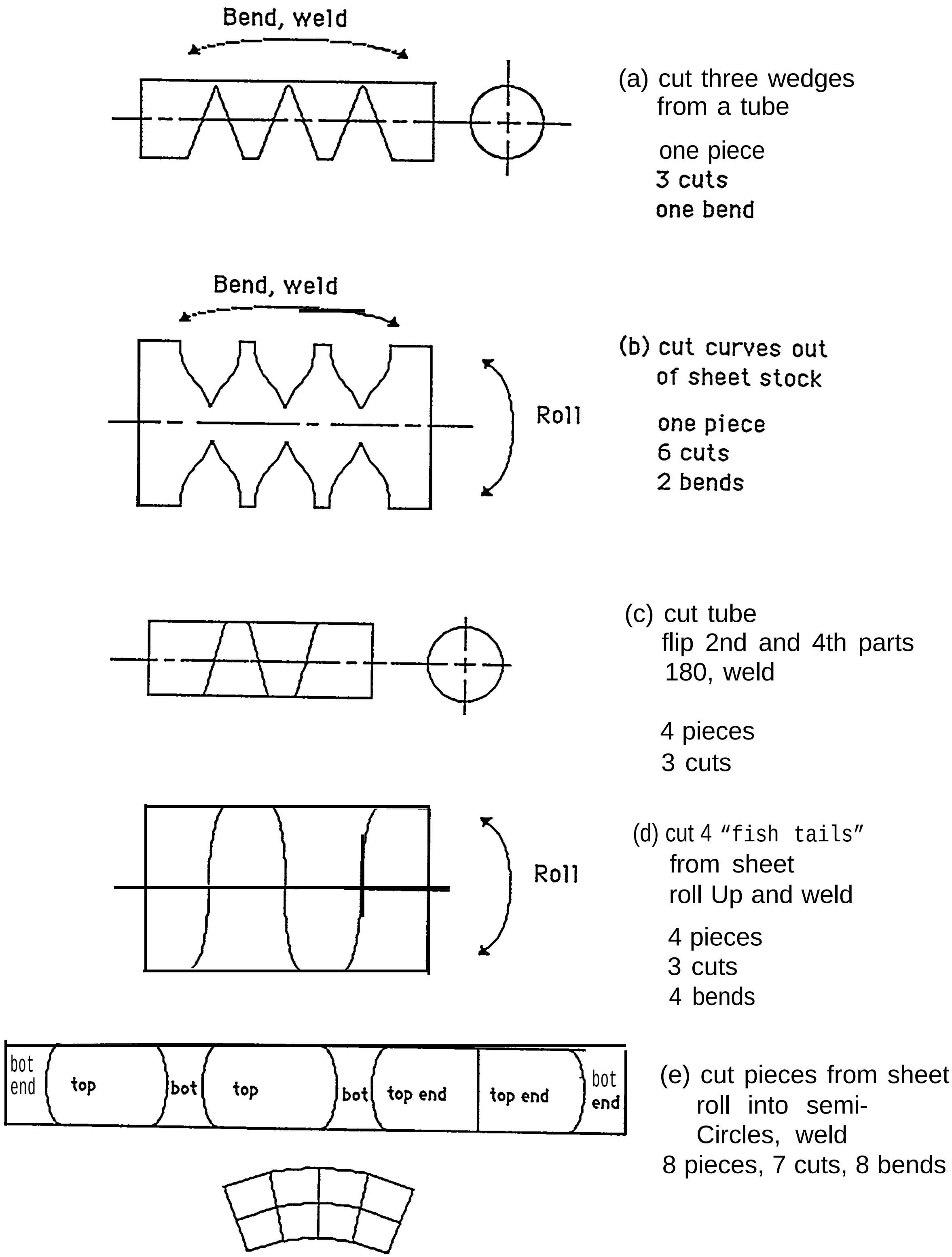


Figure IX.6

Alternate Designs for Gore-Ells

MJ structure, ladders, and insulation	12%
Lockers and furniture	12.6%
Sheet metal subcontractors	9%
Trials and deficiencies	7.6%
Small structure	1.55%
Planning	1.4%
Supervision	6.6%

2. About 18% of all welding shop charges support the sheet metal shop .

3. On average, a man-hour of sheet metal is accompanied by 0.28 man-hour of welding.

4. Detailed sheet metal shop charges were available for 9 pairs of job orders that separated vent fab from installation of the same vent pieces. For these 18 jobs, an average of 2.68 installation man-hours were required for each man-hour of fab. These jobs accounted for 39% of all charges by all trades to ventilation work.

The above data support some intriguing conclusions, although more data would be needed to add real confidence. Also, many additional questions arise.

First, sheet metal work is dominated by vent, so our focus on vent is justified. Second, since cutout of sheet metal parts is automatic, fast, and accurate, and welding is about 27% of vent sheet metal charges, it appears that most vent charges go for bending, fitting, measuring, drilling, clamping, and other manual fab or installation jobs. Finally, since "installation" of a vent piece is 2.68 times more time-consuming than its "fabrication," it appears necessary to investigate installation more deeply. Some possible discoveries are:

1. A lot of fabrication actually may occur during "installation" due to rework or interferences. This must be tempered by the

fact that the destroyer in question here was by far not the first of its class built by this yard.

2. The charges being analyzed may be inaccurate, or the words "fab" and "instal" may not mean what they appear to.

3. The vent may have been designed so that fabrication actually is incomplete and that some true fabrication on block or on board is expected. The question is whether this on-board fab is necessary.

4. A lot of "installation" time may be wasted.

No conclusions are possible from these data regarding the influence of pre-outfitting because the start and stop dates on the 18 job orders cover most of the ship's construction period, and almost all were stopped on the same day. These dates are apparently administrative and do not tell when the work really began and ended.

F. Open Questions

In our brief study, several questions have been identified but not answered. These are:

1. What changes to design philosophy or specs are possible, and what would their effect be?
2. What percent of vent, by running foot, pound, or piece count, is straight? What other statistics would be interesting?
3. What other joining methods besides arc welding are feasible? What about seam resistance welding, adhesives, sealants, or wrappings?
4. What are the real cost components of vent fab and installation? How long does it really take to install a vent piece compared to the time to make it, and how is this time

spent? How much is actually fab, fitting, measuring, installing hangers, testing, balancing, etc.?

G. Conclusions and Recommendations

1. The mechanical details of vent design are determined by detail designers and yard planners, not by the customer.
2. Space restrictions in fan rooms and overheads lead to short vent pieces, contorted runs, many changes in cross section (with pressure losses), and difficult fabrication, installation, and repair. Design traditions and, ironically, modern CAD techniques, encourage and perpetuate these problems.
3. Navy specifications for WT and DP vent lead to welding as the common fabrication method. Studies to relax both wall thickness and joint specification are under way. But their impact will be small unless the design patterns noted above can be changed.
4. A good possibility for new design techniques is to exploit the NC plasma cutter to cut out "exotic" shapes that can be bent into final shapes without a lot of intermediate fitting.
5. There is not enough cost and time information to make detailed decisions concerning new ways to design, make, or install vent.

X. FLEXIBLE AUTOMATION POTENTIAL IN PIPE

A. Introduction

Piping systems are one of the major subsystems of a ship and represent a significant percentage of the total labor required for a hull. In a naval combatant ship, for instance, piping system labor represents 15% of the total labor[1]. If material costs are considered in addition to labor costs, fabricated piping costs are approximately 25% of the total basic construction costs of a ship[2]. Piping systems thus contribute heavily to the overall cost of a vessel. Methods of increasing productivity in the entire piping system process can have major impacts on these costs.

Flexible automation in the context of piping systems does not simply mean installing a robot at an isolated station in a pipe shop . Rather, it is a systematic approach to the entire piping process from design through planning, fabrication, installation and testing. While flexible automation may tend to conjure up an image of sophisticated hardware, this approach is not entirely equipment specific. In the area of piping systems, the approach emphasizes the following:

<u>understanding the real requirements of the job</u>-- pipe design and fabrication are very old trades and many practices are continued because "they have always been done this way." It is necessary to take a detailed look at what is required versus what is practiced, especially in the areas of tolerances and standards.

<u>Investigating alternatives once the requirements are understood</u>-- new technology in materials, processes and machines can offer advantages and may suggest changes to traditional methods.

<u>Recommending solutions based on the alternatives</u>-- recommendations may be in the form of computer controlled machines, computer based software systems, reorganization of work areas to incorporate modern management and industrial engineering concepts, and alternative materials.

The remainder of this chapter discusses shipyard piping systems in light of this approach. It is organized as follows: The current practices of a typical pipe shop are first reviewed. These are discussed in the context of what was observed during visits to pipe shops at various yards. Major issues facing current piping system procedures in the context of flexible automation are then identified and delineated. The state of the art in automation is set by discussing available technologies. Finally, recommendations for future work and research are outlined. The emphasis in this chapter is on piping systems for surface ships.

B. Pipe shop Procedures

The procedures of a typical pipe shop will be broken down and discussed in four categories: (1) design, (2) scheduling, (3) fabrication and (4) installation. Detailed Piping system design is performed by either the engineering staff of the shipyard or by an outside design agent contracted by the shipyard. The scheduling of pipe system fabrication and installation is usually performed internally to the yard and concerns the sequencing and planning of work in the shop. Fabrication and installation are intimately related but will be discussed separately. Fabrication concerns in-shop manufacture of spools from individual pipe pieces, valves and other components. Installation is the process of installing individual pipe pieces or spools into a unit, block or ship.

1. Piping system design

Pipe design is an evolutionary process beginning with general notions of the system and ending with specific sizes and paths of pipes called out on drawings. The ultimate objective of the piping system designer is to determine the size, shape, material and location of pipes, valves and other components necessary to perform the required function.

Concept, preliminary and contract design of piping systems are performed by NAVSEA. The outputs of contract design are major arrangement diagrams and system specifications (flow rate, temperature, pressure). These are expressed in two types of drawings: contract and contract guidance drawings. Contract drawings are mandatory in what they specify (materials, workmanship, inspection and quality control) and can only be amended with an Engineering change Proposal (ECP), a review process involving NAVSEA and the designer. Contract guidance drawings are not as stringent and can be modified without an ECP.

Detail piping system design begins after the award of a ship contract. AS mentioned above, detail design can either be performed within a yard or by an outside agent, at the discretion of the yard. A detail designer creates a piping system that meets the arrangements and specifications of contract design. Of concern to the designer are issues of pipe size, material and layout. Design is governed by a myriad of specifications, standards, publications and drawings. The principal ones are:

MIL-STD-22D Welded Joint Design

This standard identifies and categorizes various types of welded joints for pipes. Dimensions are called out in the joint diagrams when they are important. For instance, the minimum root opening for a butt weld with a backing ring is specified to be no less than 1/4 inch for pipes greater than 3 inches in diameter (IPS).

MIL-STD-278E(SH) Fabrication Welding & Inspection

All classes of piping (P-1, P-2, P-LT, P-3) as well as machinery, pressure vessels and turbines are covered in this standard. An “Approved Weld Joint Design” table in the Design Requirement chapter refers to MIL-STD-22D in identifying allowable joints for pipe classes. This table is vague, even to NAVSEA personnel. It does not clearly specify why one joint is preferred over another. Footnotes to the table do indicate that a major concern in piping systems is crevice corrosion and certain types of welds are not allowed on materials that are subject to corrosion. Sleeve welds are allowed on pipes and fittings that are 70-30 or

90-10 copper-nickel. Inspection requirements are also detailed in this document.

MIL-STD-777D Schedule of Piping, Valves, Fittings and Associated Piping Components

This is a more general standard than MIL-STD-278E(SH). It covers the requirements for basic piping system components, primarily through a table which references applicable documents for items in every piping service category and group. The document makes specific reference to the new DDG-51 guided missile destroyer by not permitting slip-on flanges nor flaring of pipes.

MIL-STD-1627B(SH) Bending of Pipe or For for Ship Piping Systems

pipe bending, heat treatment, inspection requirements and acceptance criteria are covered in this document. Specific temperature ranges for bending and post bending operations as a function of pipe material are specified. For pipe bending it is necessary to inspect (magnetic particle or liquid penetrant) all bends of 3D and less.

There are hundreds of additional specifications and standards that a designer must pay attention to and understand. Understanding is crucial; the requirements underlying the guidelines need to be clear in order to insure a good design. An ideal design cycle should include both the exploration of alternatives and the choice of the most favorable one as well as iteration between the design and the production teams. A designer possessing intimate knowledge of the applicable specifications produces an initial design and sends it to a production engineer familiar with the processes by which individual pipe spools are fabricated. The production engineer reviews the drawing, making suggestions which would allow the spool to be produced more efficiently, with less manpower or material, for example. These suggestions should be considered by the designer as changes are made. This ideal situation does not exist universally in shipyards. If such an iterative design-production loop did exist, more producible designs should result.

Shipyard’s detail design departments (both internal and external) are under extreme pressure to complete their designs and simply do not have the time or manpower to optimize the producibility of their output. They design systems to the best of their ability given the time allotted and pass on their blueprints to the production group where the fabrication of individual spools is scheduled. In the case of follow-on ships that are constructed at different shipyards this problem is more acute. The lead yard designs systems to be produced with equipment resident in-house. Since equipment differs from yard to yard, building piping systems to the specifications of the original drawing can be difficult, sometimes impossible. The problem is further complicated by various contractual agreements that increase the amount of paperwork necessary to implement changes to systems designed by a different yard.

The pipe shops of the shipyards visited are slowly becoming cognizant of the importance of formal communication between design and production groups. Perhaps the best situation exists at Avondale's Louisiana shipyard. Avondale has a semi-automatic pipe handling and fabrication facility (described in subsection D) that is set up to handle uncomplicated pipe spools. This type of spool is ideal for the ships they are currently building. Avondale's pipe system designers have been trained to design pipe spools that can be produced with their automated hardware. They have a systematic design philosophy that emphasizes pipe spools which:

- can be cut, welded and bent on automated cutting, welding and bending machines
- consist of relatively straight pieces having few bends, branches and fittings
- consist of more overall joints (compared to other design strategies) which are easier to put together either on unit, block or on board.

Avondale designs their spools with production in mind.

In another yard the piping section has developed a "Producibility Manual" which specifies design preferences for piping systems. This manual will be sent to the yard's design agent prior to their performing detail design. In a third yard, pipe design changes were instituted in second and third ships at a point in time when pipe personnel had a firm idea of the ship's production schedule and recognized shortcomings in the original designs. Other movements toward establishing channels of communication include involving pipe shop personnel in the design loop and increasing the scope of the production department to review designs before they are issued. This involvement is critical.

2. Piping System Scheduling

The next step after detail design of piping systems is determining the sequence and timing of fabrication and installation. This process is performed in-house, usually by the manager or lead foreman of the pipe shop. Schedulers fundamentally face time and space decisions: when should various systems (fresh water, fuel, lubrication oil, etc.) be fabricated and when should they be installed (on unit, on block, or on board) so that they do not interfere with other subsystems. In addition, they typically decide where pipe systems are to be broken up (how spools are defined) produce sketches of Pipe details for use in the shop, and write material orders to receive necessary supplies from the yard's warehouse.

In making these decisions the scheduler is guided by certain rules. Some of these rules have underlying reasons: layout of particular systems are specified by contract drawings that must be adhered to, and fuel oil valves cannot withstand sandblasting and therefore must be installed afterwards. Other reasons have developed over time through experience: it is easier to install larger diameter pipes first and smaller diameters later.

Scheduling decisions for pipe shop fabrication are primarily based on experience. With a rough idea of how long certain packages require and the date they are needed for installation, the planner works backwards to come up with dates for starting fabrication, ordering material and writing material orders. Flexibility is provided by deliberately scheduling light, thereby allowing more time than necessary. Storage space compensates for the extra spools. Scheduling is not based on work content. Planners do not know how much labor and time is required for each individual spool and consequently cannot schedule based on those levels. Instead, they rely on average figures for typical spools and depend on the slack in the schedule to absorb deviations from the average. Many spools comprise a work order, and pluses and minuses often balance each other.

3. Piping Fabrication Practices

Once a piping system is designed and pipe shop work is scheduled, shop fabrication can commence. This section will review the fabrication practices of a pipe shop in a typical shipyard(3). It will do so in diagramatic form, with flowcharts shown on the following pages. Note that not all yards will have all of the equipment or steps shown in the flowcharts.

4. Installation Steps

With pipe spool fabrication completed, installation of spools and individual pieces can begin. This section will review the installation steps a pipefitter follows in installing spools into a unit, block or on board a ship(3). As in the previous section, this review will be diagramed with flowcharts, which may include steps not performed in all yards. The installation of small pipe, typically less than 1-1/2 inches in diameter ("run to suit" pipe), is also performed during this phase. These pipes are installed on board without individual shop sketches.

C. Major Issues

This section will discuss some limitations and knowledge gaps inherent in piping design, scheduling, fabrication and

FLOWCHART SYMBOLS

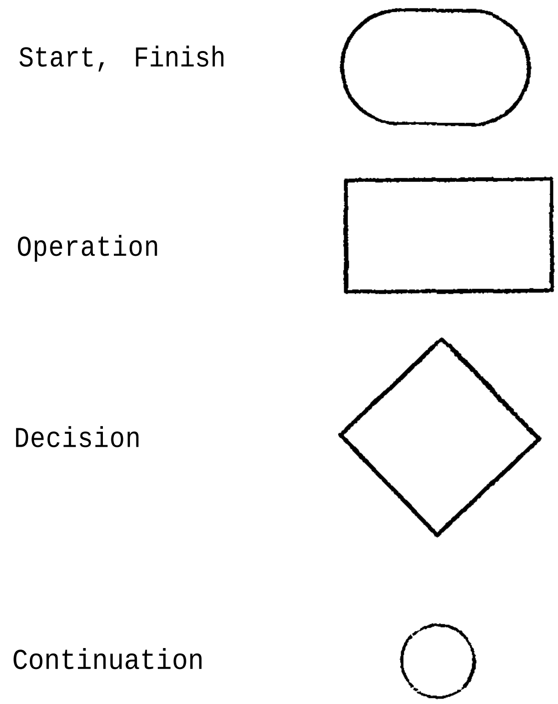


Figure X.B.1

PIPE FABRICATION STEPS

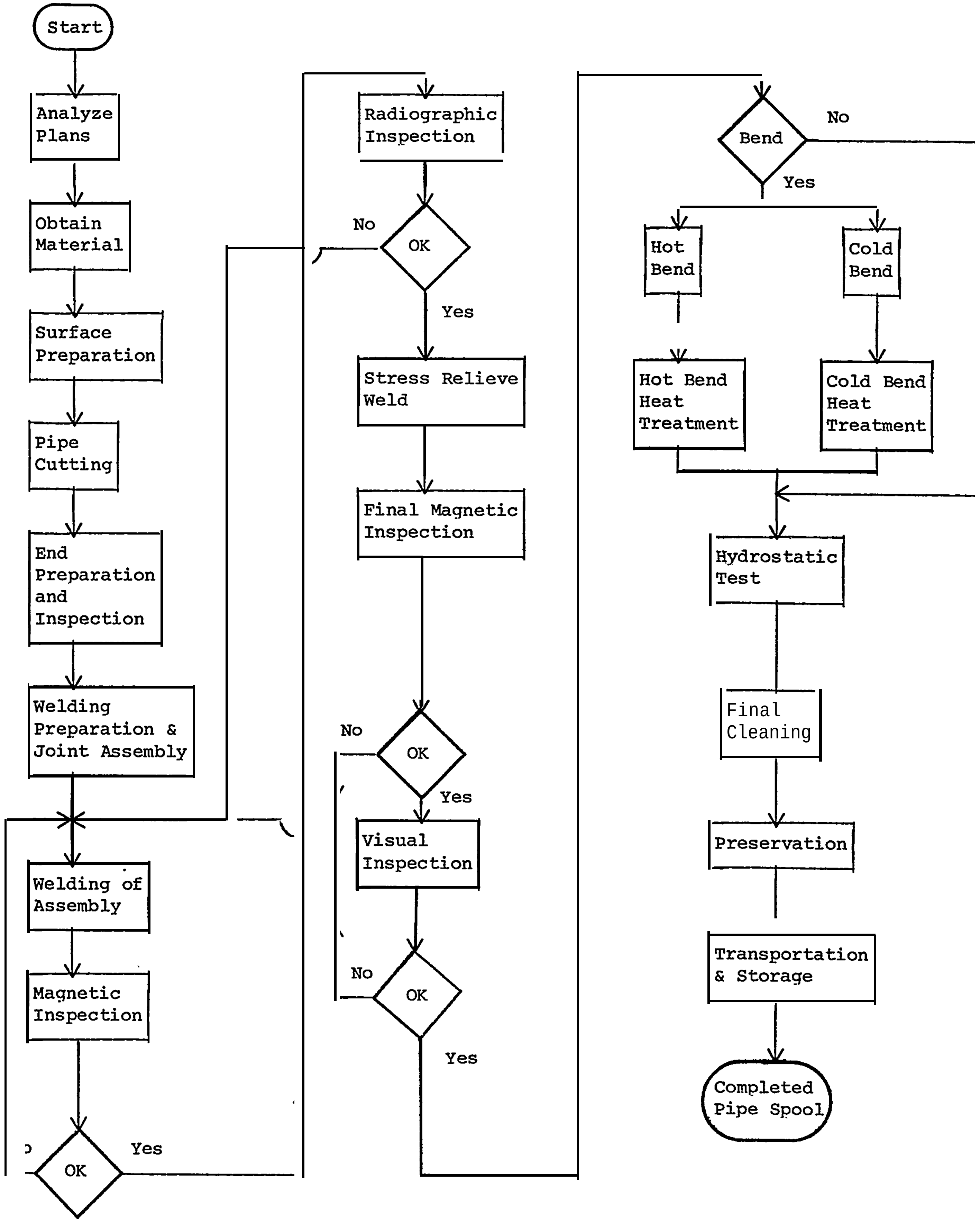


Figure X.B.2

PIPE INSTALLATION STEPS

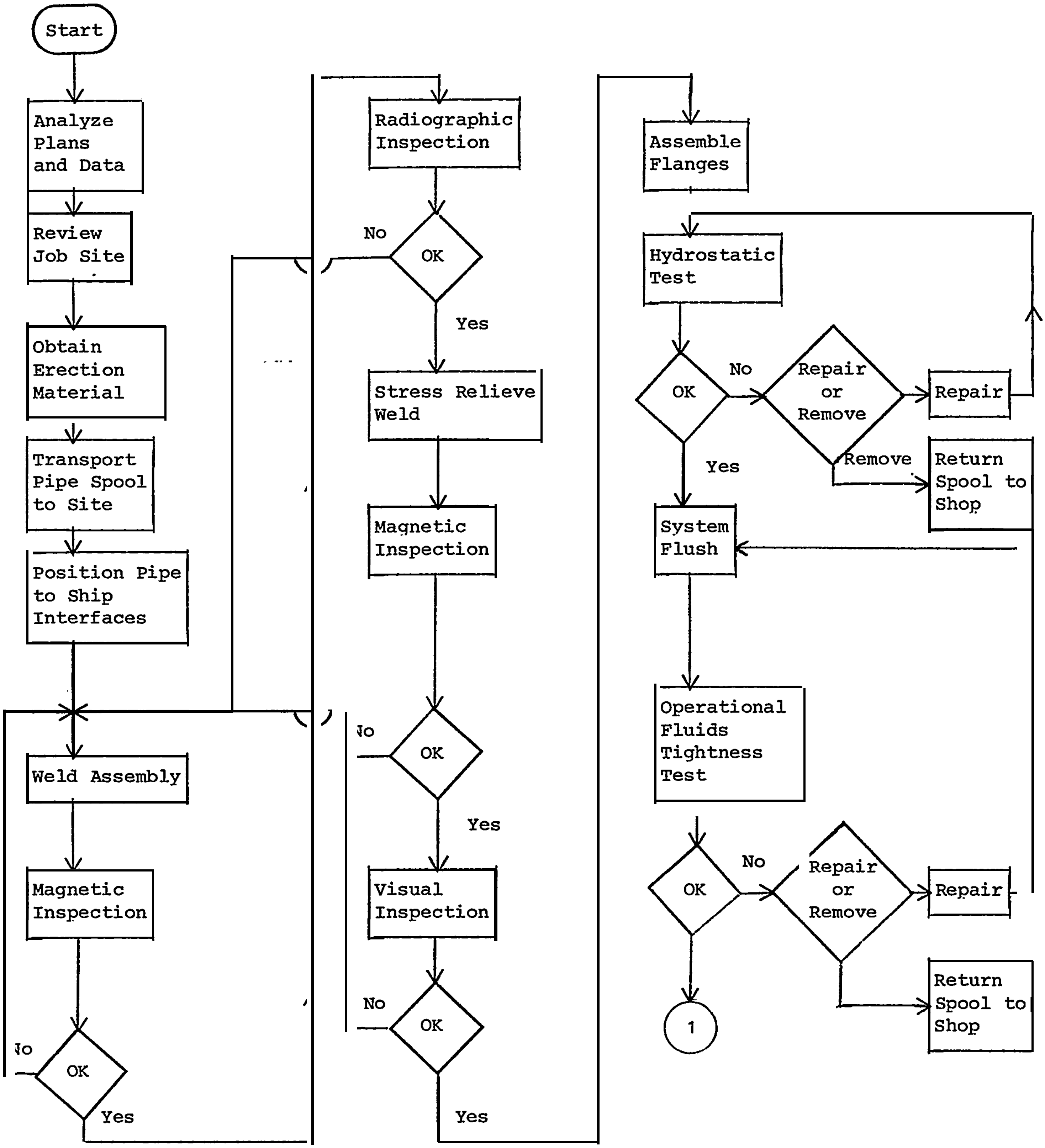


Figure X.B.3

PIPE INSTALLATION (CONT'D.)

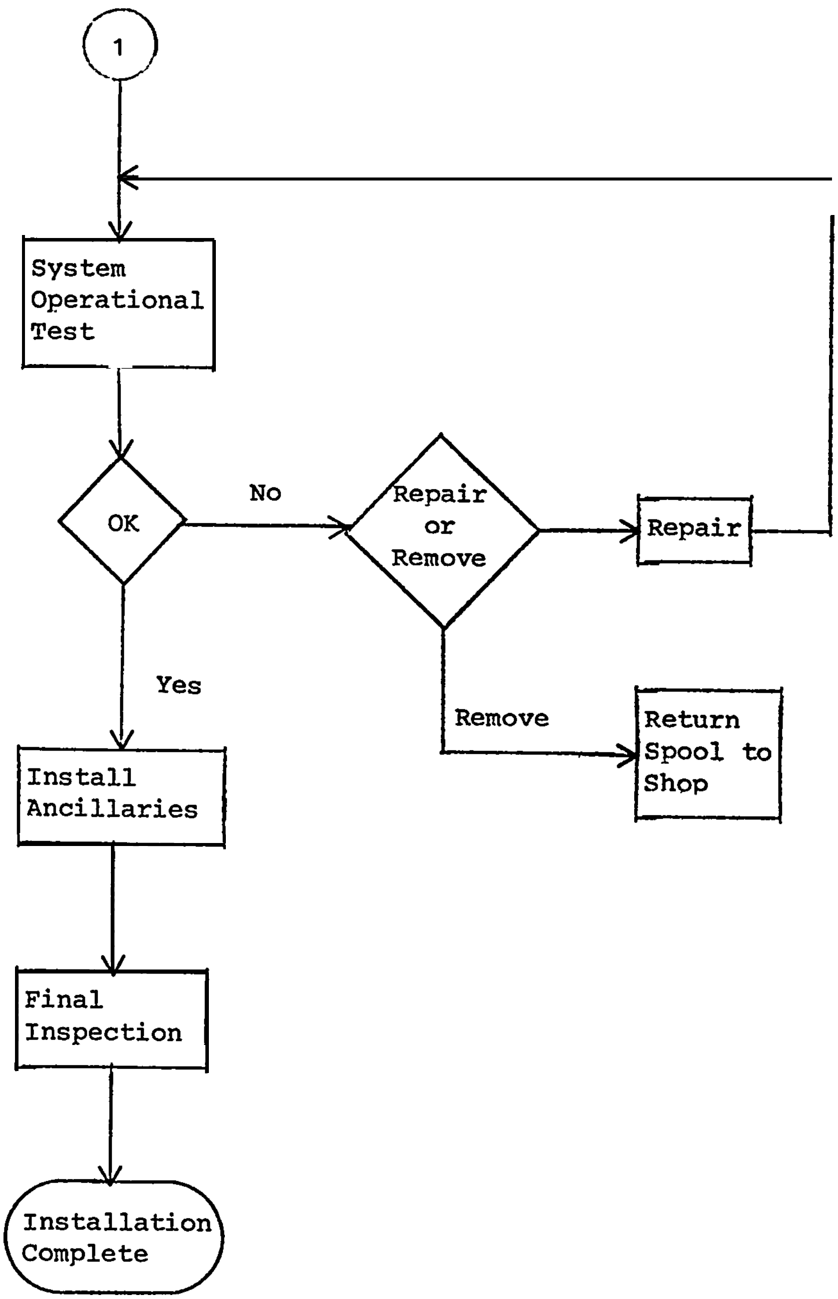


Figure X.B.3 (cont'd

installation that must be addressed before flexible automation can be successfully applied.

1. Pipe spool design and fabrication details

It is important for piping systems to be designed with production in mind. At the shipyards visited this is not universely practiced. Pipe pieces designed with ease of producibility have the following qualities:

a) Pipe design emphasizes long spools:

Currently, pipe pieces are frequently cut up into many little pieces which are in turn welded back together. A recent study of pipe in a FFG-7(4) revealed that the ship has approximately 87,000 feet of pipe, 60,000 of which are larger than 1 inch in diameter. These 60,000 feet receive 21,000 cuts and are reassembled into 10,000 spools. Thus the average spool length is about 6 feet. Longer spools mean fewer cuts and welds, but there are obvious limitations in overall length. Weight restrictions for both a crane and a man, space limitations in the surrounding regions of a ship, and the necessity for a joint at module boundaries all limit the length of a spool.

b) Pipe design and scheduling emphasizes straight pieces:

The issue here is straightforward: straight pipe pieces are easier to handle than bent pieces during fabrication and installation. This issue affects fabrication sequencing: bending of flanged pipe should occur after the flanges have been welded on. Bending after welding introduces the requirement of maintaining proper orientation between bolt holes on opposite flanges during bending. This is tricky, but can be handled by modern numerically controlled bending machines. By contrast, it is inefficient or difficult to weld flanges on bent pipe.

c) Design decision trade-offs are understood:

Designers of piping systems need to understand the ramifications of their design decisions. Design differences can have an enormous effect on the fabrication time and installation requirements of a spool, as illustrated in the following two examples:

Decisions between joint types:

Table X.C.1 lists design, fabrication and installation attributes of four types of pipe joints: but, sleeve, socket and screwed/threaded. In the case of sleeve and butt joints, both are permitted in governing documents, but they have important fabrication and performance differences. Sleeve joints are self-aligning, require two welds, a welder of average skill, cause no weld drip-through problems or flow restrictions, but increase the weight of the overall system. Butt joints need accurate alignment, require only one weld, a welder of better than average skill, and have drip-through problems and flow restrictions, particularly if a backing ring is used.

Table X.C.1.

Design, Fabrication and Installation Attributes of Joint Types

	Butt	Socket	Sleeve	Screwed
Common Use	large dia hi T&P	small dia hi T&P	small dia hi T&P	small dia low T&P
Relative Weight	lightest[1]	light	heavy	heaviest
Number of Welds	1	1	2[2]	0
Corrosion Potential	low[1]	low[3]	low[3]	high
Strength	good	30%<butt[4]	good	poor
Wall Thickness	uniform[1]	↑@ joint	↑@ joint	↓@ thread
Hanging Space	smallest	> butt	> butt	largest
Flow Resistance	minimal[1]	minimal[3]	minimal[3]	nonzero
Insulatability	easy	hard	hard	hardest
Alignment	need jigs	self align	self align	need jigs
Leak Potential	low	lowest	lowest	highest
Disassembly	difficult	difficult	difficult	easy
Assembly Cost	highest	lowest	med-high	med high
Assembly Skill	highest	medium	med-high	lowest
Joint Preparation	clean & bevel	clean	clean	tape or sealant

[1]without a backing ring

[2]sometimes an additional, internal weld is performed

[3]if fit-up is accurate

[4]reference [5]

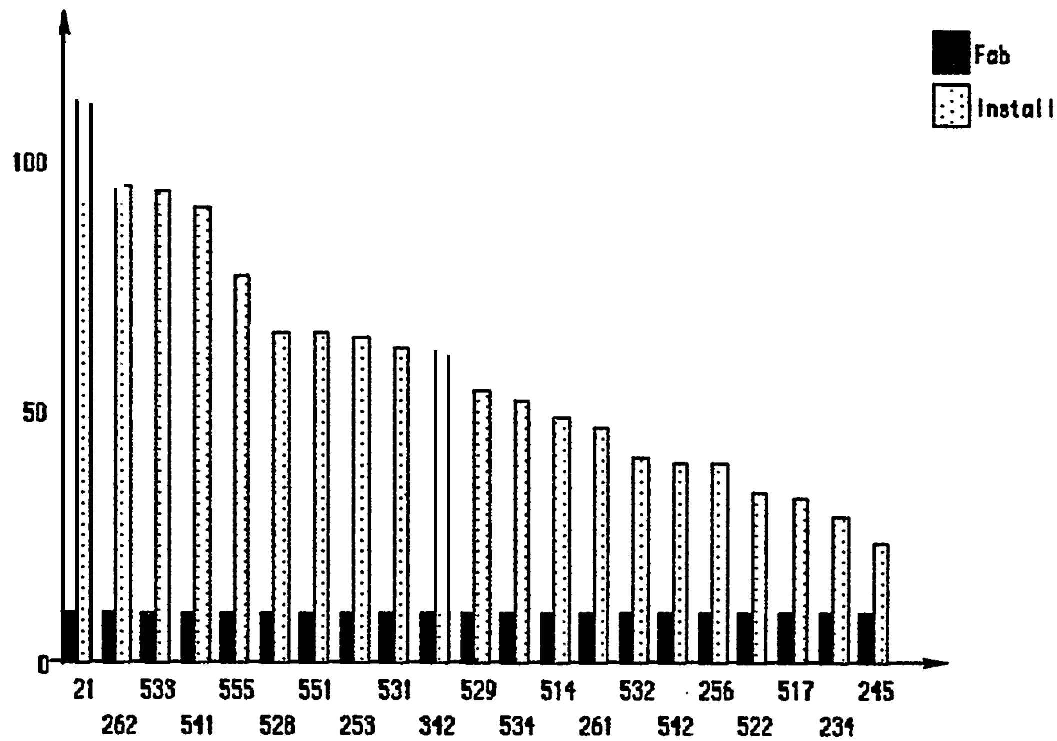
Bend radius vs. inspection requirements:

Pipe designers who strive for compact system layouts may be increasing the inspection requirements. For example, any bends of 3D or less require either magnetic particle or liquid penetrant inspection per MIL-STD-1627E(SH). Larger radii bends require only visual inspection. The designer is faced with a trade-off between system size and inspection tasks .

Other considerations of a pipe system designer should include the relative time between spool fabrication and installation. In a breakdown of fabrication and installation man-hours for twenty-one different pipe systems (over 120 job orders) on a recent destroyer the ratio of installation to fabrication time ranges from 3:1 to 11:1 depending on the system. The average is 7:1. This data is shown graphically in Figure X.C.1. Note, data is normalized to 10 man-hours fabrication time. This data covers 54% of total man-hours by all trades for the systems. Considering that most of spool fabrication takes place in the shop (except gage piping and templated pieces) and most installation takes place during preoutfitting or on the ways, it is clear that extra effort, at design time, aimed at reducing the installation to fabrication ratio can have a multiplicative effect at reducing the total labor required for a spool.

d) Pipe diameters and geometries are standardized:

Using a standard set of pipe diameters simplifies the ordering of material, eases storage requirements and reduces the number of necessary tools (mandrels used in bending, for example) and fittings. Emphasis needs to be placed on increasing the number of standardized pieces and reducing the number of custom designed ones. The use of standardized geometries and designs will increase the weight of the ship. Such an increase can be calculated in the design cycle.



RATIO OF INSTALL TIME TO FAB TIME FOR 21 SWBS PIPE GROUPS, NORMALIZED TO FAB TIME = 10

Figure X.C.1

e) System layout trade-offs are understood:

Consider Figure X.C.2 a showing an obstacle and two ends of a pipe system, A and B. It is necessary to route a section of pipe between A and B, avoiding the obstacle. There are many paths that accomplish this, two are shown in the figure. Path 1 requires two 90° bends (or elbows) and approximately 12 feet of pipe. Path 2 requires three 90° bends but only 6 feet of pipe. Which path should the designer choose? In order to make "the best" decision it is necessary to provide a designer with detailed information, principally material, process and labor cost data.

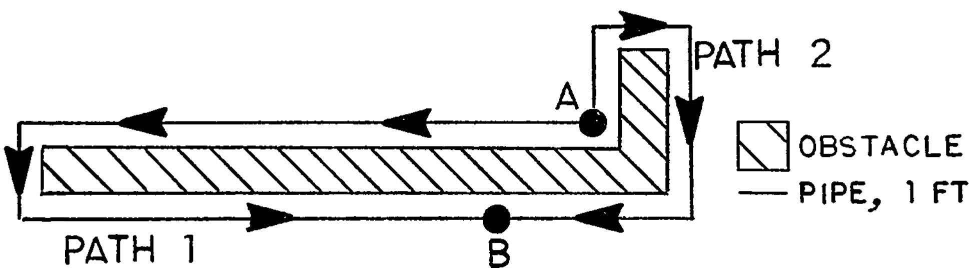


Figure X.C.2. Pipe routing decision

The answer to the design decisions and trade-offs described above is rationalization based on cost. It is first necessary to determine cost differences between alternative materials, hardware, spool characteristics, processing equipment and required labor hours, and then make the information available to the design and production teams. Gathering such data is not an easy task; understanding whether 2D pipe bends with liquid penetrant inspection requirements are overall more economical than 3D bends with only visual inspection needed requires careful monitoring and calculation. Establishing design rules based on economic data is not an overnight job, but once the rules have been established they should insure more efficient fabrication and installation of piping systems.

2. Scheduling of Pipe Shop Work

Scheduling of work through the pipe shop typically relies on the experience of the shop planner. This reliance achieves the result of pushing the pieces through the shop, but not necessarily in the most efficient or economical manner. Fabrication scheduling is generally not based on work content. Some spools take longer to produce than others, but how much longer and what the extra time does to the labor loading across the shop are not known. Fabrication sequences are usually set by the design of the spool, but not always (bend vs weld in flanged pipe, for instance). Shop level loading is critical to an efficient production. Improper scheduling can lead to excessive levels of work in progress, clogged workstations, and extra inventory and storage, all of which lead to increased costs.

3. Physical Arrangement of Shop

The physical arrangement of machines and workstations in a pipe shop has a major impact on material flow through the shop. The characteristics of well laid out shops are that pipe piece movements are straight, occur in a single direction, are of minimal distance and occur in a palletized carrier(5). In addition, the transfer of raw pipe into and finished spools out of the system should be orderly and convenient. Efficient workstations have sufficient workspace with the necessary tools available and handy. Internal shop storage areas need to be large enough to store a week's worth of work without becoming conjested(6). The prerequisite of such an organized shop is a well understood, standardized and scheduled pipe fabrication process.

4. Tolerances and Accuracy Control

Pipe fabricators produce spools in accordance with the designs shown in their working sketches, but how accurately they do so is not always known. The accuracy problem is two-fold: fabricators typically have a poor understanding of tolerances, and pipe systems depend on the accuracy of other items, primarily structural, which are not necessarily reliable. The result is that installing pipe requires maneuvering and muscle. “If it doesn’t fit, force it” is a common motto among pipe fitters.

Design and accuracy are inherently related. The more stringently a design is enforced, the more accurately it will be built (ideally). Most yards side step design and accuracy issues by designing “fudge factors” into their spools. Some yards build excess length into their spools; one yard leaves excess on as many as 30% of their spools(7). Yards also make use of templated pipe pieces, small pipes that connect machinery units to other pipes. They are extremely labor intensive since they require a person to visit the connection site on board the ship and construct a model of the connection piece (by bending a small pipe or tack welding small pieces together) which in turn is individually fabricated in the shop. Excess length and templated pieces are necessary since the locations of other pipe systems or machinery foundations are not reliable. These practices are decreasing in yards, fortunately so since they perpetuate inaccurate workmanship and result in unnecessary labor.

Accuracy control is a widely talked about but seldom implemented method of statistical quality assurance. The basis of an accuracy control system is well defined and performed work practices on well designed pipe pieces. If a pipe shop is to be competitive, it is necessary for it to understand the accuracy of its output, the areas of reduced accuracy and the reasons for and solutions to those problem areas.

5. Cost Accounting Practices

The cost accounting practices at the yards visited are organized along functional lines rather than by individual pipe spool or system. That is, various general accounts are charged as spools are processed as opposed to charging against the spool itself. At one yard the assistant pipe foreman explained which accounts get charged for which portion of the pipe shop work. The breakdown is shown graphically in Figures X.C.3a and X.C.3b. Both "white collar" and "blue collar" accounts are charged during spool fabrication. white collar labor is basically paperwork: sketching, writing shop orders and scheduling, as shown in Figure b. Blue collar labor is dominated by fitup and tack followed by welding and brazing. Figure X.C.4 shows that only 46% of the total man-hours per pipe spool are directly charged to the spool. The remaining percentage is charged to the ship, welding and pipe shop .

Of all the additional crafts that support pipe fabrication and installation, welding is dominant, from a cost viewpoint. In a breakdown of cost charges for a similar ship to that represented in Figure X.C.4 each hour charged to pipe fabrication and installation accounts was accompanied by 15 minutes of welding charges. All in all, 17% of the total welding shop charges goes to supporting pipe fabrication and installation.

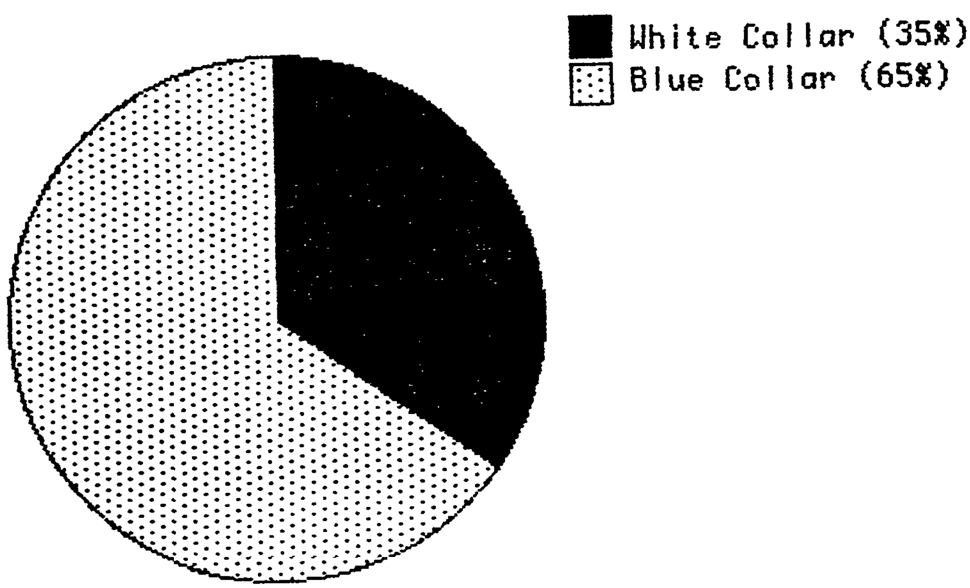


Figure X.C.3a. Distribution of estimated cost for pipe spool fabrication

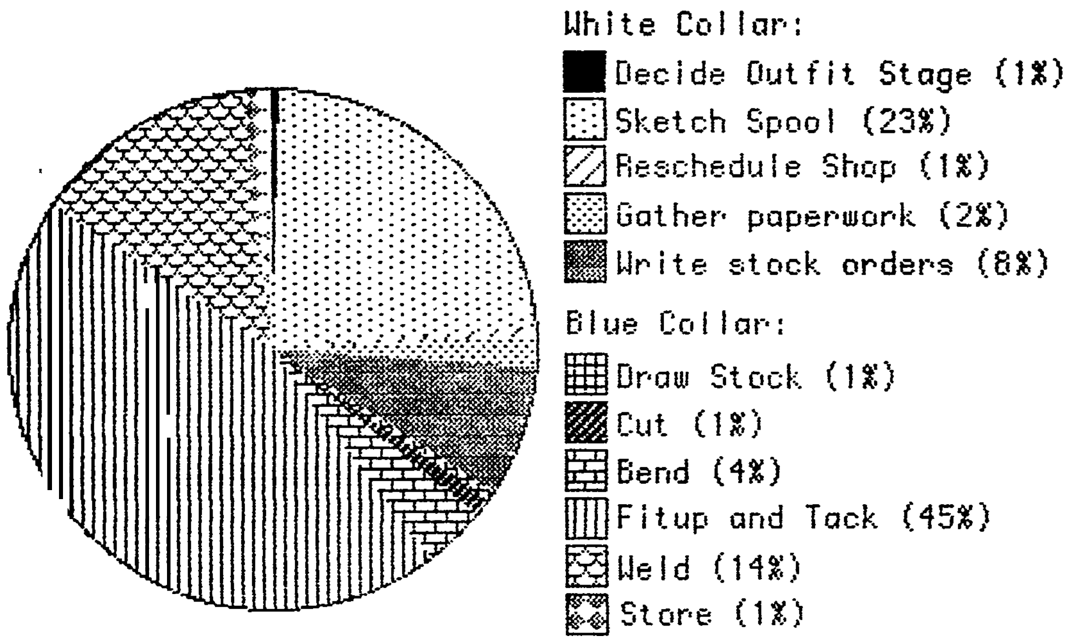


Figure X.C.3b. Breakdown of white collar versus blue collar labor in pipe spool fabrication

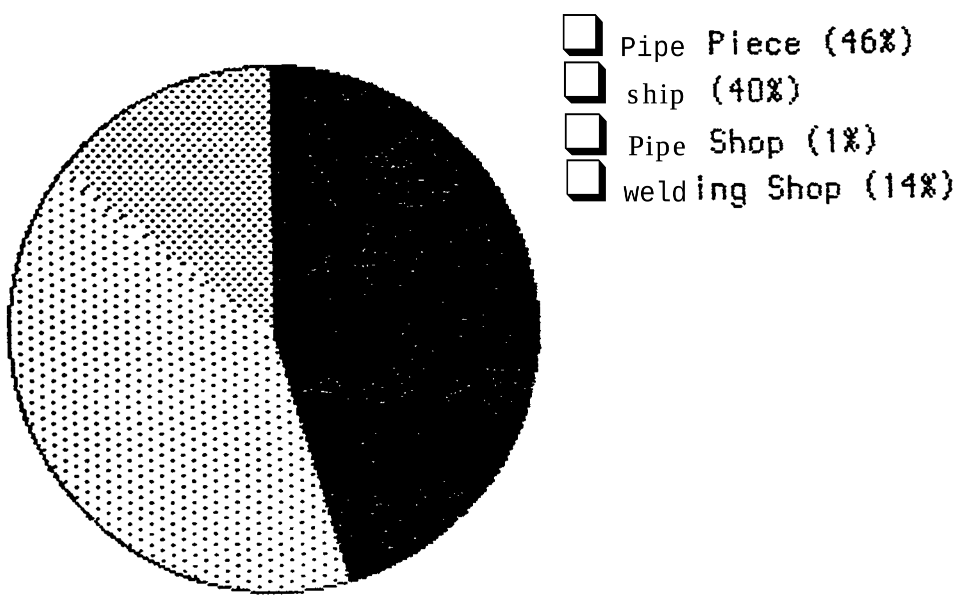


Figure X.C.4. Distribution of accounts that are charged the cost of fabricating a pipe piece

These practices of charging various trade accounts instead of pipe pieces themselves make it difficult to get an accurate accounting of what it really costs to fabricate a specific spool. Without knowing individual spool costs and the contributions from each trade, trade-offs between materials, spool definition and sequencing cannot be realistically determined.

6. pipe shop output variance Among yards

It is interesting to note the differences of pipe shop output among the different yards visited. Table X.C.2 shows five yards, the extent to which they are automated, and an estimate of their efficiency expressed as man-hours required per pipe spool. The highly automated yard is obviously more efficient than the others. What is interesting to note is the wide variation of manhours per spool between the first four yards. Yards 1 and 3 build similar or identical ships, as do yards 2 and 4. It is unclear why labor variation is so pronounced. Differences in shop layout and efficiency of operations are obviously important factors.

Table X.C.2. Pipe Shop Output for Five Yards

Yard	Extent of Automation	Manhours/spool
1	bender	7-8
2	bender, process lanes?	5.1
3	semi-auto bender	4.6
4	semi-auto bender	9
5	highly automated	3

7. Variance of Allowed practices Among Yards

Not only do pipe fabrication labor efficiencies vary among the yards visited, but allowed practices differ as well. Consider the example of extruded branch bosses in pipes. Yard A is permitted to extrude bosses only on large diameter pipes. Yard B has NAVSEA'S approval for small diameter pipes. An independent pipe supplier processes pipe in a similar manner for an intermediate size range. Yard A can buy extruded boss pipe from Yard B, Yard B can buy A's and both can buy from the supplier. Resolving a situation such as this requires communication and cooperation between different yards and the Navy.

8. Technology phobia

Shipyards have been aware of the benefits of technology, but only recently are taking steps to integrate them into their yards. The older attitude that "shipyards are different" is slowly beginning to change. The publication of the new Journal of Ship Production and increased communication between yards through the annual Ship Production Symposium are indicative of new attitudes. Yards are recognizing that with world competition, increased cost of and shortage of skilled labor, and tight delivery schedules, new ideas and methods need to be welcomed.

The blame for the yard's sluggish attitude toward change lies on the shoulders of both the industry and the Navy. The principal drawback with the current mechanism for change is that it is extremely long and unrewarding. Whether it is a design enhancement to a contract drawing or the qualification of a new pipe welding method, change is paperwork intensive, burdensome and lengthy. The incentive for change is overall cost saving for the yard (and the customer), but savings are quickly eradicated by delays and additional work. What is needed is a formal mechanism wherein ideas can be submitted, and tested, and decisions can be made in a structured and timely manner.

9. Vendor Standardization and Marine Equipment

Some of the biggest headaches shipyards experience are caused by equipment suppliers. Standardization among vendors in piping materials, notably valves and fittings, is poor. Each supplier has different size valve stems and handles. These variations require the specification of unnecessary details at detail design time and complicate the purchase of equipment; both practices are costly. The Navy's insistence on using marine equipment in lieu of pipe industry equipment with equivalent performance also inflates the cost of piping systems.

D. State of the Art in Flexible Automation

This section reviews the state of the art in flexible automation in piping systems. Flexible automation refers not only to machines but also includes computer systems, software and manufacturing management ideas. All of these areas will be covered.

1. State of the Art in Pipe Processing Hardware

Much of the pipe processing hardware specified below is in place at Avondale's Louisiana yard(2) and many foreign shipyards (7).

a) Raw pipe storage:

pipe elevators are racks or silos in which pipes of necessary diameters are stored horizontally. Automatic loading and unloading systems allow storage and selection of pipe to proceed without manual intervention. Avondale's system of selecting pipe, loading them onto conveyors and transporting them to the desired workstation is all pushbutton controlled. Their silos store pipe in a diameter range of 1-1/2 to 24 inches in various wall thicknesses.

b) Pipe transfer:

Conveyors are favored over cranes for pipe transfer since they are less limited by weight capacity and pipe complexity.

Automatically guided vehicles and robo-carts used to transfer material between workstations are being employed in modern aerospace manufacturing plants and may be applicable in shipyards.

c) Measurement and cutting:

The functions of measuring and cutting pipe can be integrated into a single machine. Pipes can be placed on the feed mechanism of a machine which advances them to the desired cut length. Cutting machines can be of several types: plasma torch, band saw or abrasive cutoff saws. Plasma torch has an advantage over saws in that it can produce a bevel. More sophisticated equipment, in place at Avondale, can produce contoured holes for saddles and branches.

d) Surface cleaning and end preparation:

The cleaning of pipe ends prior to the welding of flanges and/or fittings can be accomplished with boring mills or pipe lathes. Lathes are versatile since they can handle a wide range of diameters. Other smaller devices include portable grinders and specialty end preparation tools. These lightweight devices have the advantage of less set-up time and greater flexibility, especially with larger, harder-to-maneuver pipe. Avondale uses an alternative cleaning system, using both internal and external surface preparation booths which shotblast the surface.

e) Welding:

Automatic welding machines for both flange and branch welds exist and are in routine use, notably at Avondale. Flange welding machines select the flange, orient it properly, tack it into place, and perform both internal and external welds. Automatic welding machines operate by either rotating the pipe under a fixed welding head or by rotating the head around the diameter of the pipe. Straight pipe is usually rotated, while branch and fitting welds are performed with the pipe stationary and the welding head in motion. Avondale has a branch extruding machine which can extrude 90° tees into the sidewalls of pipe. Another welding machine then welds a piece to the extruded section.

f) Bending:

Sophisticated numerically controlled (NC) bending machines can handle complex and multiple bends on pipe sections. Two U.S. manufacturers, Teledyne Pines (8) and Conrac,[9] offer numerically controlled cold form horizontally drawn bending machines with the following capabilities:

- 3 axis bends: distance between bends, rotation of pipe between bends, and bend angle are programmable

- minimum bend radii of ID

- pipe diameter range from 1 to 10 inches

- maintenance of flange orientation during bending

NC machines of this type can be linked to computer aided design systems which allows the translation of drawings to fabrication details to proceed without manual intervention.

2. Computer Based Systems Packages

a) Computer aided design systems:

Current computer aided design (CAD) systems are capable of modelling three-dimensional piping components, detecting interferences with other piping and non-piping systems, producing multiple orientation drawings, and producing nongraphic lists. One system, Computervision's 4000,[10] has libraries of piping specifications (MIL-STD-777) and design rules which are checked at design time to insure that the designer produces acceptable packages. Other systems may have similar capabilities.

One difficulty with CAD piping systems is that a staggering amount of information is nongraphic in nature. pipe dimensions, material types, processing information and part numbers are only a subset of the information that must be included with every drawing. CAD systems, consequently, need to have an enormous database capability in order to process this additional information. This problem has been recognized by CAD companies who are now supplying more computer horsepower to handle the extra data.

b) Computerized pipe routing systems:

A natural extension of CAD systems, which house geometric data, is a pipe routing system, which determines the paths pipes take between points in three-dimensional space. An effective routing system uses geometric data from pipe structure, ventilation and electrical systems to determine possible interferences. Routing systems have received attention in the shipbuilding industry, (11) but no systems are known to be operational. Such systems are in routine use in a smaller scale for the layout of electrical paths in printed circuit boards. Perhaps they can serve as a basis for piping arrangement systems.

c) Scheduling and planning software systems:

Automatic scheduling and planning of shipyard activities is natural for a computer. Scheduling can occur for all facets of the shop: ordering materials, planning the work, level loading the shop, accounting, to name a few. Computerized systems also serve the function of collecting labor and schedule time for work packages. This data can subsequently be used to determine the work content of an individual pipe package, which can be used to adjust scheduling of shop fabrication.

3. Industrial Engineering and Manufacturing Management Concepts

a) Group technology:

Group technology (GT) is a systematic method of classifying products into families which have similar design and manufacturing attributes (12). In terms of pipe systems it makes sense to group similar spools together so they can be manufactured as a batch, thereby achieving some of the benefits of quantity production. Ideally a GT code for piping systems should include the following information:

pipe diameter

material

bend information: number & radii of bends

number of welds (brazes)

inspection information

complexity of spool: number of joints

processing details: sequence of operations, type of workers needed

A well developed GT code can achieve several benefits including computerized sorting, workload balancing, work content estimating, accounting, and scheduling. An excellent discussion of GT coding for shipboard piping systems is found in [1]. NASSCO has instituted a coding scheme based on a subset of the list above(13). They predict the adoption of the code along with a reorganization of the pipe shop, will result in 100% improvement in pipe spool productivity.

b) Process flow lanes:

A process lane is a series of workstations that have fixed services (electrical, welding) and the necessary tools to produce products that have similar processing steps and requirements (12). Process lanes can be set up to handle families of pipe spools once those families have been identified through group technology coding. With process lanes a pipe shop employee at a station can perform similar work (end preparation, for instance) on various diameter pipes and quickly become adept at his task.

c) Just in time:

The phrase “just in time” refers to a method of inventory management wherein material is in inventory only shortly before it is required. It does not sit in storage for weeks ahead of time, taking up valuable space. A prerequisite for such a material management scheme is a thorough understanding of what is required and when it is needed. It requires the consistent support of material suppliers in order to operate effectively. It is not clear how closely yards schedule the arrival of material and fabrication steps which require it.

E. Recommendations for Future Work

The investigation of piping system practices has been limited in scope in this study. This section details some areas for future work that are necessary to explore further before the application of flexible automation for piping systems can move one step closer to reality.

1. Better Understanding of Piping System Design

Emphasis is placed on the design cycle since a majority of the fabrication and installation timing and costs are determined at the designer’s table. The most important step aspect of well understood pipe design is detailed cost information. With it, decisions between types of joints, location of pipe breaks in spools, optimal spool lengths, range of acceptable tolerances, least costly system arrangement, in addition to other design and fabrication alternatives, can be made on a rational basis.

With such design understanding, specific design rules for a yard and ship type can be established: use sleeve joints for pipe connections in the diameter range of 1-1/2 to 4 inches, butt joints beyond 4 inches, for instance. Designers can subsequently be trained to follow such rules. The purchase of new equipment can be considered if, according to cost data, it results in economic savings.

2. Exploration and Adaptation of New Technology and Alternative Methods

Shipyards are currently facing a “catch-22” concerning new technology and equipment: they desperately need them in order to remain competitive on a global scene, but the business horizon is not encouraging enough to justify major capital investment. It is not an easy predicament that has a single magic answer. Yards can, however, begin to make inroads in small steps. They need to continually encourage new ideas and adopt well-conceived plans.

One of the most promising areas that requires modest investment and offers a potential of great return is the increased use of computerized systems, notably the personal computer. One such system, described at the 1985 NSRP Ship Production Symposium, is a computerized tool list(14). This system eliminates wasted travel time from shop to ship by providing a craftsman with a complete list of tools he needs before he leaves the shop. The payback period of a pilot program implemented at Ingalls Shipbuilding was approximately 3 months. Computerized systems of this type can be focused on specific problem areas and be developed by a small team, often by a single person.

Other alternate methods and new ideas more specific to piping systems include: 1) optimizing the bevel angle for welded branch pipe construction. Typical angles are held constant around the periphery of the branch. Changing the angle as a function of pipe radius, intersecting angle, wall thickness and centerline offset can reduce the total volume of weld required by up to 500%, while maintaining total weld penetration. This material savings translates into reduction in total welding time. It is straightforward to alter standard cutting machines so they can produce variable cut angles on a pipe. 2) the possibility of using lightweight plastic or fiberglass reinforced pipe (17) where non-corrosive, low-pressure, low-temperature fluids are handled. These pipes are weaker under stress than their metal counterparts, but nevertheless may have wide application. This area merits further study. In the oil cargo piping and clean ballast systems of a 90,000 DWT tanker, fiberglass reinforced piping offers cost savings over steel systems of 15% and 20%, respectively(17). 3) integrating pipe jigging and measurement methods for many diameter pipes in the pipe installation phase. This would coalesce two independent activities into one. 4) investigate the limitations of flexible couplings between pipe and machinery connections. Flexible couplings may be able to replace labor intensive templated pipe pieces for some machinery connections.

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XI. INITIAL ECONOMIC ANALYSIS OF SNIP OUTFITTING

Introduction

Building a ship is more like constructing a building than manufacturing a product. The usual quantities for a batch of work are less than 100; often they are less than 10. As a result, the normal cost accounting methods used for manufacturing are not easily applicable.

The major difficulties in shipbuilding appear to arise from data, schedule and logistics. Some yards have made significant steps into automating the design and resulting data which affects the scheduling as well as the logistics. Interferences for example can be found at the design stage instead of on the module or ship. Coordination of all materials and workers so that they are in the right place at the right time is a significant job. Part of this activity requires better control over inventory (this is an apparent goal of the new Navy purchasing plan). An accurate way of tracking (and altering when necessary) all this activity would be a significant contribution to lowering the cost of building ships.

There are technological issues in shipbuilding as well. Two important conditions keep automation from being readily applied:

size - available equipment not large enough.

economics - small quantities, except for reasonable similarity in pipe, vent and electrical shops.

The size issue can only be attacked piecemeal whereas the economics issue is pervasive and potentially resolvable.

Can a rational method for establishing present costs and yields (ratios of actual throughput to optimum throughput) be established? If so, can improvements in yield which reduce cost be instituted? This chapter describes a method for doing both. It will show that automation can be justified by means other than labor replacement.

Economic Justification Principles

Every procedure for accomplishing tasks has fixed costs and variable costs. Each company uses its own (internally generated) values for annualized cost of capital equipment and for the burden applied to labor rates (and possible operating/maintenance rates). For present purposes, we will assume that these parameters are known.

Justification of an alternative scheme for doing the tasks must show that, compared to a base method, savings in variable costs occur. Such savings will presumably flow in over a number of years. One fundamental issue in finance is that a dollar n years from now has, with respect to today, a value discounted at an appropriate (Internal) rate-of-return (r):

$$\$_0 = \$_n/(1 + r)^n \tag{1}$$

A commonly used evaluation method, known as net-present-value, determines how well a proposed investment compares to the discounted savings stream. It is usually only valid when depreciation, taxes and credits are also included.

We have devised a technique based on zero present worth (or value) which allows an engineer to determine how much he can invest for a prescribed internal rate of return(1). This technique has been programmed and will run on any IBM-PC compatible computer. It takes in estimated savings data and outputs allowed investments based on a range of internal rates of return (Figure 1) or a particular rate (18% is used in Figure 2). The data chosen for these examples are quite arbitrary but may be similar to shipyard conditions. Actual savings data can easily be entered and the results readily evaluated. Estimating the savings that a proposed automation project could generate is thus the crucial task facing the engineer.

Determination of Savings

Establishing the expected savings appears to be an easy task. Unfortunately, most automation justifications look at only the labor content of tasks to be performed and assume that most of it can be replaced. Even manufacturing companies are prone to make this simplification. A convenient way to express variable (or process) cost is(2):

$$C_v = \frac{(t_{cyc}/y)}{3600} (W \bar{L}_H + O_H) q \qquad (2)$$

where

t_{cyc} = ideal cycle time (seconds/unit)

y = yield rate (actual output/theoretical output)

3600 = second/hour

W = number of workers required

$\bar{L}_H$ = average burdened labor rate ($/hr)

O_H = system operating/maintenance rate ($/hr)

q = quantity to be produced (unit)

This equation is applicable to both the present or base method and the proposed alternative methods for accomplishing the tasks.

The difference (base C_v - alternative C_v) establishes the savings expected.

How might the alternative scheme's variable cost be less than that for the base? Any (or combinations) of the following should be accomplished:

1. **reduce ideal cycle time (t_{cyc})**
2. increase yield rate (y)
3. decrease number of workers (W)
4. **lower burdened labor rate ($\bar{L}_r$)**
5. **lower operating/maintenance rate (O_r)**

When talking about shipbuilding, the only factor whose change is probably significant is yield. It is also the factor most likely to be undocumented since it tends to be absorbed into work standards.

Precise methods for improving yield depend upon the particular situation. The following sections describe techniques for economically evaluating the outfitting of a ship. Some portions of the development will be generally applicable to all phases of shipbuilding.

Outfitting a Ship - A Three Level Process

When putting components into a ship, the builder has three levels from which to choose

1. On unit
2. On blocks
3. On board

Costs increase significantly from level 1 to level 3 usually due to the fact that any job takes longer to perform and that there is much more likely to be interference with components already in place.

The discussion below is based on our prior work on failure/yield analyses.(3) The goal of the analysis is to predict how much extra time or cost is needed in a multi-level process when failures could occur at each level. Example failures include a pipe not fitting, or vent interfering with structure, and so on. In general, a failure could require that the work repeat the current level, or that the work return to a previous level and start over. The analysis described below assumes that failures only have to repeat the current level or part of it. Thus, if a pipe piece does not fit On a unit it is fixed at the unit and does not have to be rebuilt in the shop.

We will analyze a single level first, and then multiple levels. The goal is to quantify how much can be saved by reducing failures, especially in the later levels.

Single Level Process

Every process has three major cost centers:

1. Materials cost (M) - value-added to the point where the process starts.

2. Process cost (P) - the cost incurred for performing the process correctly.

3. Rework cost (R) - the (often undocumented) cost incurred when normal processing is interrupted (e.g. failed test, parts do not fit, machine downtime, wait time, etc.)

The ideal variable cost (with no rework) can be expressed by

$$C_T = q\ (M + P) \tag{3}$$

where q is the number of work pieces in a batch.

When interruptions occur, we can say that the process requires rework. In general, there will be added costs due to the rework and the fact that all those units must be processed again. Another interpretation of this phenomenon is that excess time is required to actually complete the processing of the batch of work pieces. For either case, numerical values can be attached to M,P and R which will allow specification of actual total cost to theoretical total cost for prescribed yield rates. All the mathematics are included in Appendix A; the result is repeated here:

$$T = 1 + \left(\frac{1 + R/P}{1 + M/P}\right)\left(\frac{1}{y} - 1\right)\left(1 - \frac{1}{q}\right) \tag{4}$$

where T = (actual total cost)/(ideal total cost). Note that T must be greater than or equal to 1, and 1 is the best case.

R = rework cost

P = process cost

M = materials cost

Y = nominal yield rate, that is, the fraction of work that is right the first time and does not require rework.

q = units in batch

From equation (4), we can draw some conclusions about the effect of the parameters (assume that P must be accomplished):

1. If the system performs perfectly (y=l), then T=l.

2. The less q is, the lower T will be.

3. The higher (R/P) is, the larger T will be.

4. The higher (M/P) is, the smaller T will be.

5. M could equal zero, producing the highest T possible.

Reference to Figures 3 and 4 will readily show this behavior. Note that the vertical scale is quite different for the two cases exhibited.

Application to Ship Outfitting

We would like to know the cost of outfitting a ship with a given set of materials. It is generally agreed that the higher the level at which outfitting occurs, the greater the cost. Only qualitative data is presently available but it can certainly be useful for understanding the sort of conditions which do exist and which might be vastly improved. TO illustrate the method, we will use the following ratios:

Level	Assumed (Total) Relative Cost
1 (On Unit)	1
2 (On Blocks)	3
3 (on Board)	10

This general data must be supplemented by materials, process and rework cost information for each level.

Since we are dealing with the assembly of a set of parts (materials), the M (materials cost) will be assumed constant. It is likely that the process cost (P) increases with level since complexity of the required work probably increases. Thus the ratio M/P decreases with increasing level. In Figure 5, we let $P_1 = 1000$, $P_2 = 1500$, $P_3 = 3000$ and $M = 2000$, which results in:

$$M/P_1 = 2, \quad M/P_2 = 4/3, \quad M/P_3 = 2/3$$

The cost of rework (R) probably increases with level even more than process cost (P) since it probably involves more complex disassembly and repair. In Figure 5, we let $R_1 = 1500$, $R_2 = 3000$, $R_3 = 7500$ which results in:

$$R_1/P_1 = 3/2, \quad R_2/P_2 = 2, \quad R_3/P_3 = 5/2$$

With this data as the base, we can use techniques described mathematically in Appendix A which have been put into computer program SHIPYRDY and produce results as shown in Figure 5. If we want to know the effective yields at levels 2 and 3 if the relative costs are 1:3:10, we must specify the value of the yield for level 1 and the number of items in the batch. Examination of Figure 5 reveals:

Level	Assumed Relative cost	Rework Ratio	Total Process Ratio	Resulting Yield
1	1	0.09	1.09	0.900
2	3	1.74	2.74	0.324
3	10	4.65	5.65	0.152

The reason for the significantly higher costs for higher levels is a combination of the cost for each rework and reprocess and the number of times each occurs.

If we retain the M/P and R/P values, but somehow could reduce the relative costs for level 2 from 3 to 2 and level 3 from 10 to 3, we observe dramatic improvements in yield. Figure 6 shows :

Level	Assumed Relative cost	Rework Ratio	Total Process Ratio	Resulting Yield
1	1	0.09	1.09	0.900
2	2	0.90	1.90	0.481
3	3	1.06	2.06	0.440

AS many other cost conditions as necessary can be investigated. The general result will always be: the higher the yield, the lower the cost.

If we decide to specify the yield we want and calculate the relative cost, we can use program SHIPYRDC. Suppose that the yields are:

$$Y_1 = 0.900, \qquad Y_2 = 0.750, \qquad Y_3 = 0.600$$

Figure 7 (using the prior M/P and R/P values) reveals:

Level	Assumed Yield	Rework Ratio	Total Process Cost Ratio	Resulting Cost Ratio
1	0.900	0.09	1.09	1.077
2	0.750	0.28	1.28	1.358
3	0.600	0.56	1.56	2.164

By increasing the yield, the expected cost ratio drops dramatically. Recall, from equation (4), that ratios M/P and R/P also exert considerable influence.

Suppose that all levels had a yield of 0.900. All rework/reprocessing data is constant, but costs are different. Figure 8 exhibits the slight cost ratio variance between levels even though the M/P and R/P ratios vary considerably.

The significant result is that more is gained by raising the yield and less from reducing the individual process costs and/or rework costs. Exactly how this yield can be raised is unknown at this time. In general, yield improvements must come from the specification of the work itself, the details of the various components, the scheduling, and the real-time control of the processes.

Savings Due to Increase in Yield

For any process, we can estimate the expected cost by manipulating T from equation (4) and C_v from equation (2). It can be shown that the materials cost is, and should be, independent of the process yield. The yield shown in equation (4) will henceforth be called nominal yield while the yield in equation (2) will be called usable yield; they are not usually equivalent. Figure 9 displays the behavior for a production quantity of 6 units; other production volumes exhibit similar characteristics.

Let’s determine some potential savings for level 2 (on blocks). Figure 5 shows a nominal yield of 0.3244 when R/P = 2 and Qty = 6. This data produces a usable yield of 0.1611 which can be used in equation (2) to find actual cost. The theoretical process cost is $1500. If we assume that 25 workers are required at $30/hr and the operating/maintenance rate is $20/hr, equation (2) can be manipulated (assume Y=l for now) to find the cycle time to be 7013 seconds or 1.95 hours. When we divide this value by the yield (.1611), we find that the process time is actually 12.09 hours and the actual cost is $9311 per unit. When 6 units are required, the total cost is about $56000. Now let’s assume that some means exists (better data, scheduler, better measurements, or new machines etc.) which improves the yield to 0.9000 without changing R/P and Qty. The usable yield is calculated to be 0.7826 which establishes the required time at 2.49 hours and the cost per unit at $1917. The total cost (6 units) is then $11500, a savings of $44500 (almost 80%).

We can now determine whether this amount of savings is enough to justify an investment in the alternative means for accomplishing the process. Using the numbers above, we can obtain results such as shown in Figure 10. For this situation, the alternative always has a lower unit cost. However, the allowable investment is quite small (e.g. $77k for an 18% Internal Rate of Return). The most important way to boost the allowable investment is to increase production volume. For the shipyard case, we might have the 6 unit build repeated 3 times (the same activities, or some that are very similar) thus making a total requirement of 24 units per year. Figure 11 exhibits the results; of particular note is that an 18% IRoR has an allowable investment of $309k which is probably the price class for the hardware/software required to improve the yield.

This example is only one of hundreds which occur in a shipyard. When taken in clusters, the yield improvements do not need to be quite as dramatic as in the example above in order to make significant cost reductions in shipbuilding. The methods shown here can be readily applied to any shipyard situation.

SUMMARY

An approach to understanding the costs of building a ship has been described. Only cost ratios have been used since they are easier to estimate; their sensitivity can be readily determined. Methods have been shown for cost analyzing a single level process and for comparing costs for the three levels of outfitting a ship. Utilization of the techniques allows direct cost comparisons. The savings generated by decreasing process cost, decreasing rework cost and increasing yield can be immense. Those savings are possible through proper use of an automated data base, a planning system, and an on-line tracking system. Precise cost data is not available to us and will definitely be yard specific.

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E X A M P L E F O R A L L O W A B L E I N V E S T M E N T

ZERO PRESENT WORTH CASH FLOW ANALYSIS 08-21-1986

5 YEARS OF ECONOMIC LIFE, SALVAGE VALUE 0 % OF COST

	EXPENSE FORECAST			INCOME FORECAST			
YEAR	RATIO	TAX RATE	DEPRECIABLE	SAVINGS	DEPRECIATION	TAX RATE	CREDIT
0	100.00%	0.0%	45. 0%				
1				60.000	15. 0%	42.0%	8.0%
2				63. 600	22. 0%	42.0%	
3				67.416	21.0%	42.0%	
3*				SALVAGE VALUE	42. 0%		

RATE OF RETURN	ALLOWABLE INVESTMENT	DEPRECIABLE INVESTMENT	APPROX. BRK-EVEN	CAPITAL RECOVERY	NET PROFIT
10.0	124.435	55.336	2. 90	34.248	27.992
11.0	121.286	54.579	2.84	34.390	30.088
12. 0	118.279	53. 226	2.78	34.524	32. 089
13.0	115.405	51.932	2.72	34. 650	34.001
14.0	112. 656	50.695	2.67	34.768	35.831
15.0	110.023	49. 510	2.61	34. 880	37.582
16.0	107.500	48.375	2.56	34.986	39. 261
17.0	105.080	47.286	2.51	35.085	40.871
18.0	102.757	46.241	2.47	35. 179	42.417
19. 0	100.526	45.237	2.42	35.268	43.901
20. 0	98.381	44.272	2.38	35.352	45.328
21.0	96.318	43.343	2.34	35.432	46.701
22. 0	94.333	42.450	2.30	35. 507	48.022
23. 0	92. 421	41.589	2. 26	35. 578	43.294
24. 0	90.578	40. 760	2.22	35.646	50. 521
25.0	88. 800	39. 960	2. 18	35.709	51.703
26.0	87. 085	39.188	2.15	35.770	52. 844
27.0	85.430	38.443	2.11	35.827	53.946
28.0	83.831	37. 724	2. 08	35.881	55. 010
29.0	82. 285	37.028	2.04	35.932	56. 038
30.0	80.791	35.356	2.01	35.981	57.033
31.0	73.345	35.705	1.98	36.027	57.395
32.0	77.945	35. 075	1.95	36.071	58.926
33.0	76.530	34.466	1.92	36. 112	59.828
34.0	75.278	33.875	1.89	36. 152	60.701
35. 0	74. 005	33. 302	1.86	36.183	61.548
36.0	72.772	32.747	1.83	36.224	62. 369
37.0	71.575	32. 209	1.81	36.258	63. 165
38.0	70.414	31.686	1.78	36.289	63.937
39. 0	63.286	31.179	1.76	36.319	64.688
40. 0	68.1'32	30.686	1.73	36.348	65.416

Figure 1

E X A M P L E   F O R   A L L O W A B L E   I N V E S T M E N T

ZERO PRESENT WORTH CASH FLOW ANALYSIS   08-21-1986

5 YEARS OF ECONOMIC LIFE, SALVAGE VALUE 0 % OF COST

	EXPENSE FORECAST			INCOME FORECAST			
YEAR	RATIO	TAX RATE	DEPRECIABLE	SAVINGS	DEPRECIATION	TAX RATE	CREDIT
0	100. 00%	0. 0%	45. 0%				
1				60.000	15. 0%	42. 0%	8. 0%
2				63.600	22. 0%	42. 0%	
3				67.416	21.0%	42. 0%	
3*				SALVAGE VALUE	42. 0%		

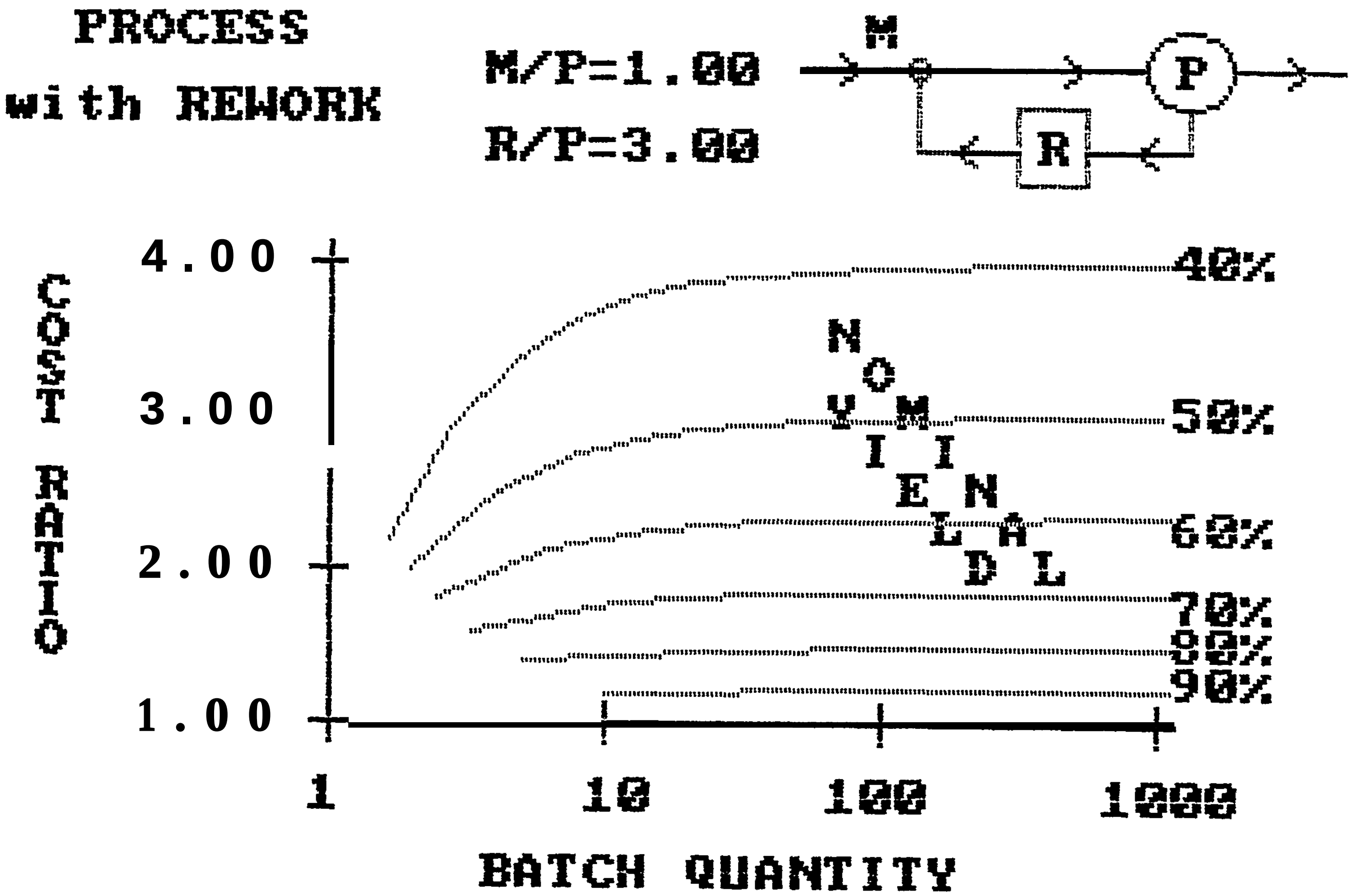
ALLOWABLE TOTAL INVESTMENT = 102.757
DEPRECIABLE INVESTMENT = 46.241
INTERNAL RATE OF RETURN = 18. 00%

PRO-FORMA CASH FLOW

YEAR	INCOME	DEPRECIATION	TAXES	CREDITS	NET	DISC. NET
0	-102.757	0.000	0.000	0.000	-102.757	-102.757
1	60. 000	6.'336	22.287	3.699	41.412	35. 095
2	63.600	10.173	22.433	0.000	41.161	29. 561
3	67. 416	9.711	24.236	0.000	43. 180	26. 280
3*	19.421	0. 000	0.000	0.000	13.421	l1.820
INCOME TOTALS	210.437	26.820	68.962	3.699	145. 174	102.757
NET TOTALS	107. 680	26.820	68.962	3.6'39	42.417	0. 000

NOMINAL CAPITAL RECOVERY = 35.179
PAYBACK IN APPROXIMATELY 2.5 YEARS

Figure 2

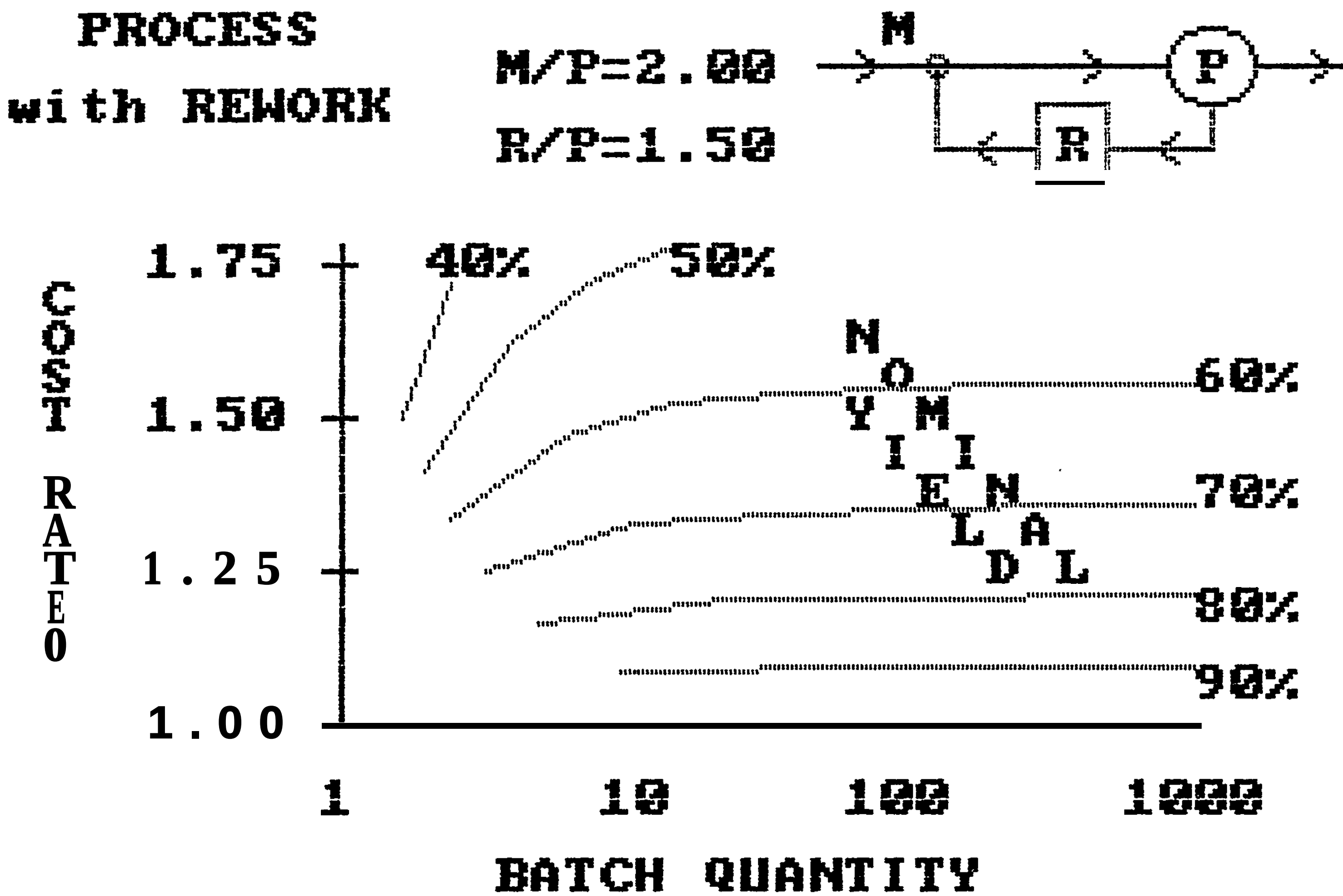


M = materials cost

P = processing cost

R = reworking cost

Figure 3



M = materials cost

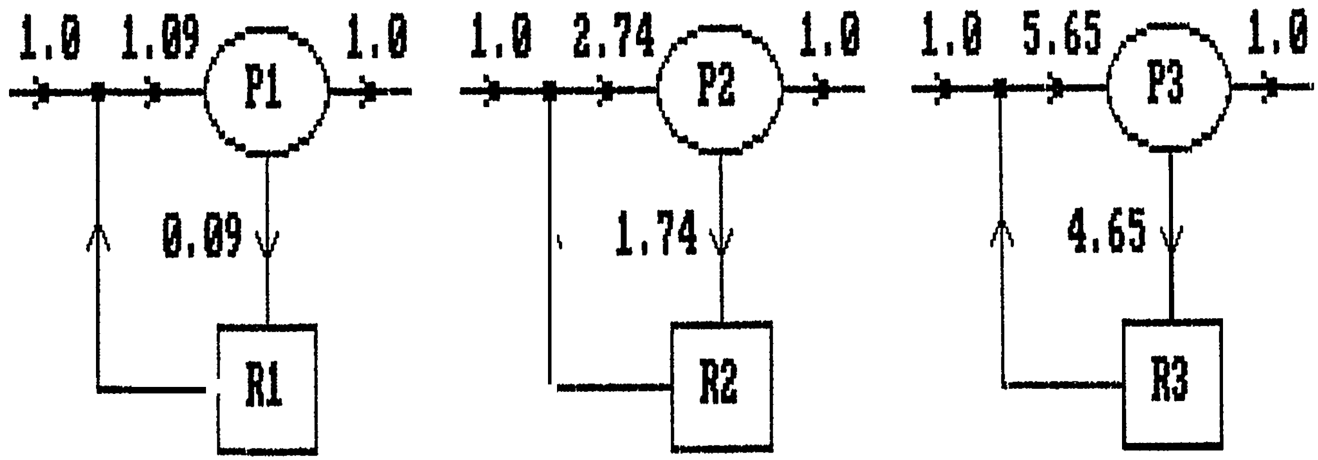
P = processing cost

R = reworking cost

Figure 4

SHIPYARD RELATIVE COST ANALYSIS 6 ITEMS

	ON UNIT	ON BLOCKS	ON BOARD
REL COST:	1.00	3 00	10 00
REW/PRC:	1.50	2.00	2.50
MTL/PRC	2.00	1.33	0 67

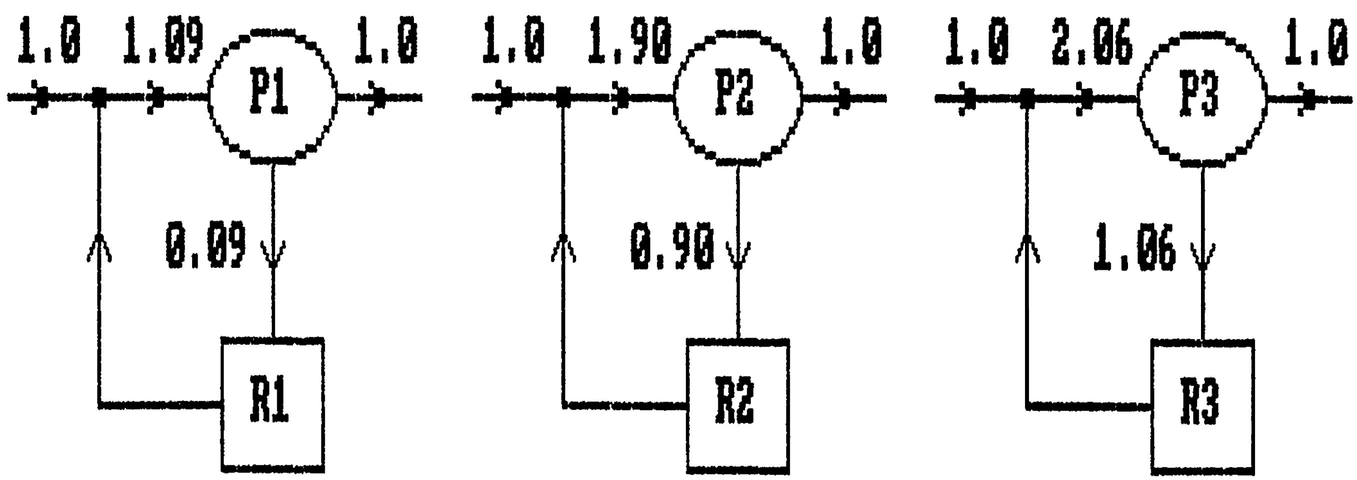


YIELD	0.9000	0.3244	0.1519

Figure 5

SHIPYARD RELATIVE COST ANALYSIS 6 ITEMS

	ON UNIT	ON BLOCKS	ON BOARD
REL COST:	1.00	2.00	3.00
REW/PRC:	1.50	2.00	2.50
MTL/PRC:	2.00	1.33	0 67

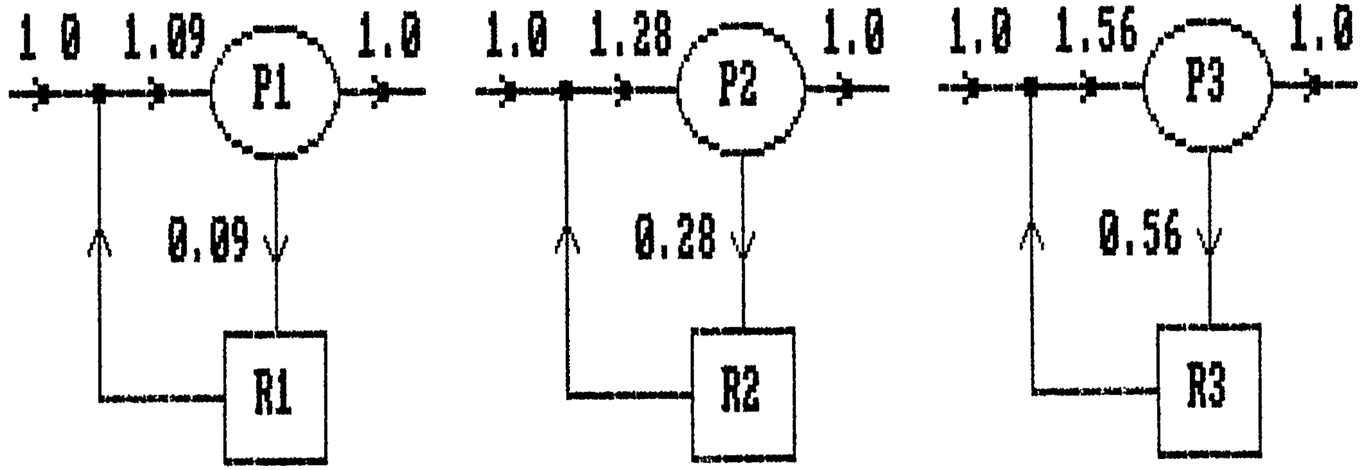


YIELD:	0.9000	0.4814	0.4395

Figure 6

SHIPYARD RELATIVE COST ANALYSIS 6 ITEMS

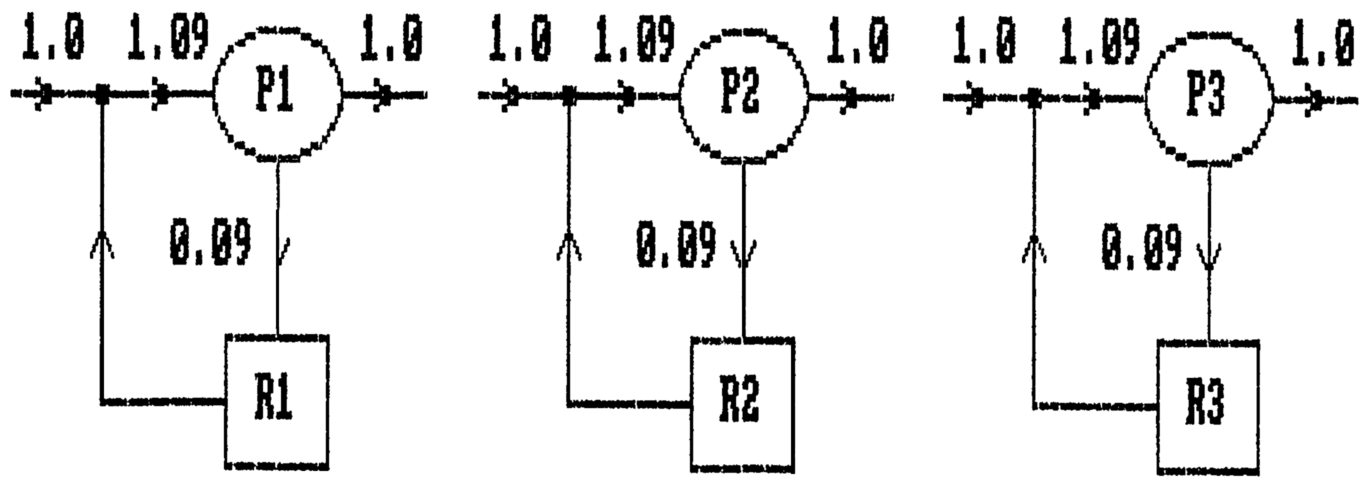
	ON UNIT	ON BLOCKS	ON BOARD
YIELD:	0.9000	0.7500	0.6000
MTL/PRC:	2.00	1.33	0.67
REW/PRC:	1.50	2 00	2.50



COST :	1.077	1.358	2.164

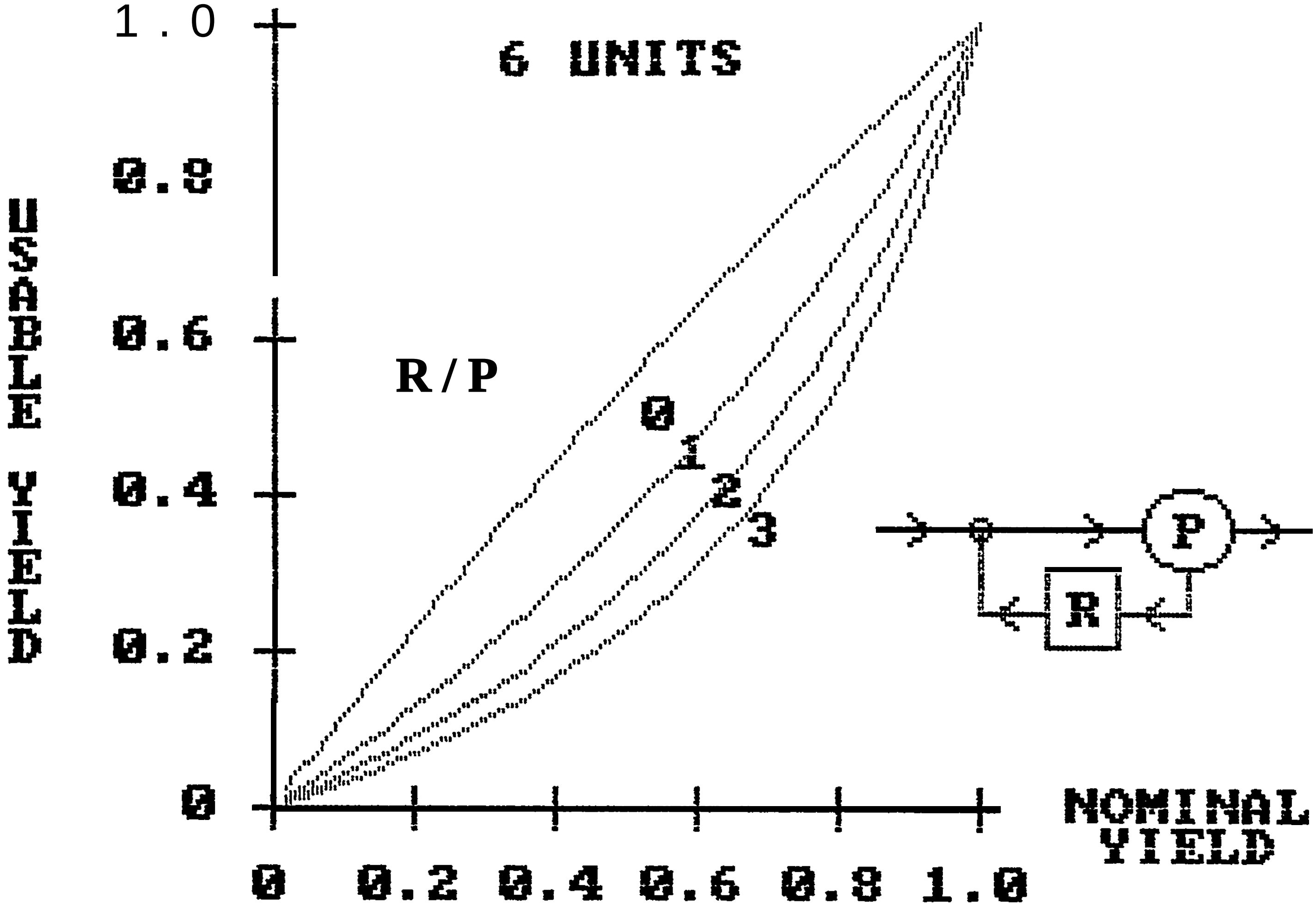
SHIPYaRD RELATIVE COST ANALYSIS ≤ ITEMS

	ON UNIT	ON BLOCKS	ON BOARD
YIELD:	0.9000	0.9000	0.9000
MTL/PRC:	2.00	1.33	0.67
REW/PRC:	1.50	2.00	2.50



COST :	1.077	1.119	1.194

Figure 8



YLD(u) = 1 / [1 + (1 + R/P)*(1 - 1/Qty)*(1/YLD(n) - 1)]

P = processing cost

R = reworking cost

Figure 9

6 UNITS LEVEL 2 (ON BLOCKS)

MANUFACTURING COSTS 02-19-1986

240 WORKING DAYS PER YEAR
1.0 SHIFTS AVAILABLE
0.0 % ANNUAL INCREASE IN PRODUCTION
8.0 % ANNUAL COST INCREASE
3 YEAR RECOVERY OF CAPITAL EXPENSES
45.0 % OF TOTAL COST IS DEPRECIABLE
0.o % TAX RATE IN YEAR 0 FOR EXPENSED INVESTMENT

COMPETING SYSTEM SPECIFICATIONS

		BASE	ALTERNATIVE
WORKERS REQUIRED PER SHIFT		25.0	25.0
AVERAGE LOADED LAB0R RATE ($/HR)		30.00	30.00
OPERATING/MAINTENANCE RATE ($/HR)		20.00	20.00
ACTUAL SYSTEM CYCLE TIME (SEC)		43532.0	8961.0
MATERIAL COST ($/UNIT)		2000.00	2000.00
EXPECTED MATERIAL REJECT RATE		0.0%	0.0%
YEARLY SPACE ALLOCATION COST ($)		0	0
YEARLY INSTITUTIONAL COST ($)		0	0
ANNUALIZED FIXED COST ($)		5000	?
YEAR 1	VARIABLE COST ($/UNIT)	9311.011	1916.658
	FIXED COST ($/UNIT)	833.333	?
	MATERIAL COST ($/UNIT)	2000. 000	2000. 000
	TOTAL	12144.344	
YEAR 2	VARIABLE COST ($/UNIT)	10055.892	2069.991
	FIXED COST ($/UNIT)	833.333	?
	MATERIAL COST ($/UNIT)	2160.000	2160.000
	TOTAL	13049.225	
YEAR 3	VARIABLE COST ($/JNIT)	10860.363	2235.590
	FIXED COST ($/UNIT)	833.333	?
	MATERIAL COST ($/UNIT)	2332.800	2332.800
	TOTAL	14026.496	

1 YEAR NET COST SAVINGS REQUIRED

CASH FLOW PARAMETERS

YEAR	UNITS	SAVINGS	DEPRECIATION	TAX RATE	TAX CREDIT
1	6	44366	15.00%	42.0%	8.0%
2	6	47915	22.00%	42.0%	
3	6	51749	21.00%	42.0%	
3*	SALVAGE VALUE		42.00%		

Figure 10(a)

ALTERNATIVE SYSTEM - UNIT COST

RATE OF RETURN	ALLOWABLE INVESTMENT	APPROX. PAYBACK	ANNUAL COST	YEAR 1 6	YEAR 2 6	YEAR 3 6
10%	933716	2.90	25793	8215.501	8528.834	8867.233
12%	89059	2.78	25995	8249.141	8562.473	8900.873
14%	84806	2.67	26173	8278.869	8592.201	8930.602
16%	80907	2.57	26331	8305.203	8618.535	8956.936
18%	77322	2.47	26471	8328.568	8641.901	8980.301
20%	74014	2.38	26596	8349.339	8662.672	9001.071
22%	70953	2.30	26707	8367.822	8681.156	9019.555
24%	68115	2.23	26806	8384.288	8697.621	9036.021
26%	65476	2.15	26894	8398.966	8712.299	9050.698
28%	63017	2.09	26972	8412.055	8725.389	9063.787
30%	60720	2.02	27042	8423.731	8737.065	9075.463
32%	58571	1.96	27105	8434.144	8747.477	9085.876
34%	56556	1.90	27161	8443.424	8756.758	9095.156
36%	54663	1.85	27210	8451.691	8765.025	9103.424
38%	52883	1.79	27254	8459.049	8772.383	9110.781
40%	51205	1.74	27294	8465.586	8778.918	9117.318
42%	49621	1.69	27328	8471.381	8784.715	9123.113
44%	48125	1.65	27359	8476.510	8789.842	9128.242

6 UNITS LEVEL 2 (ON BLOCKS)

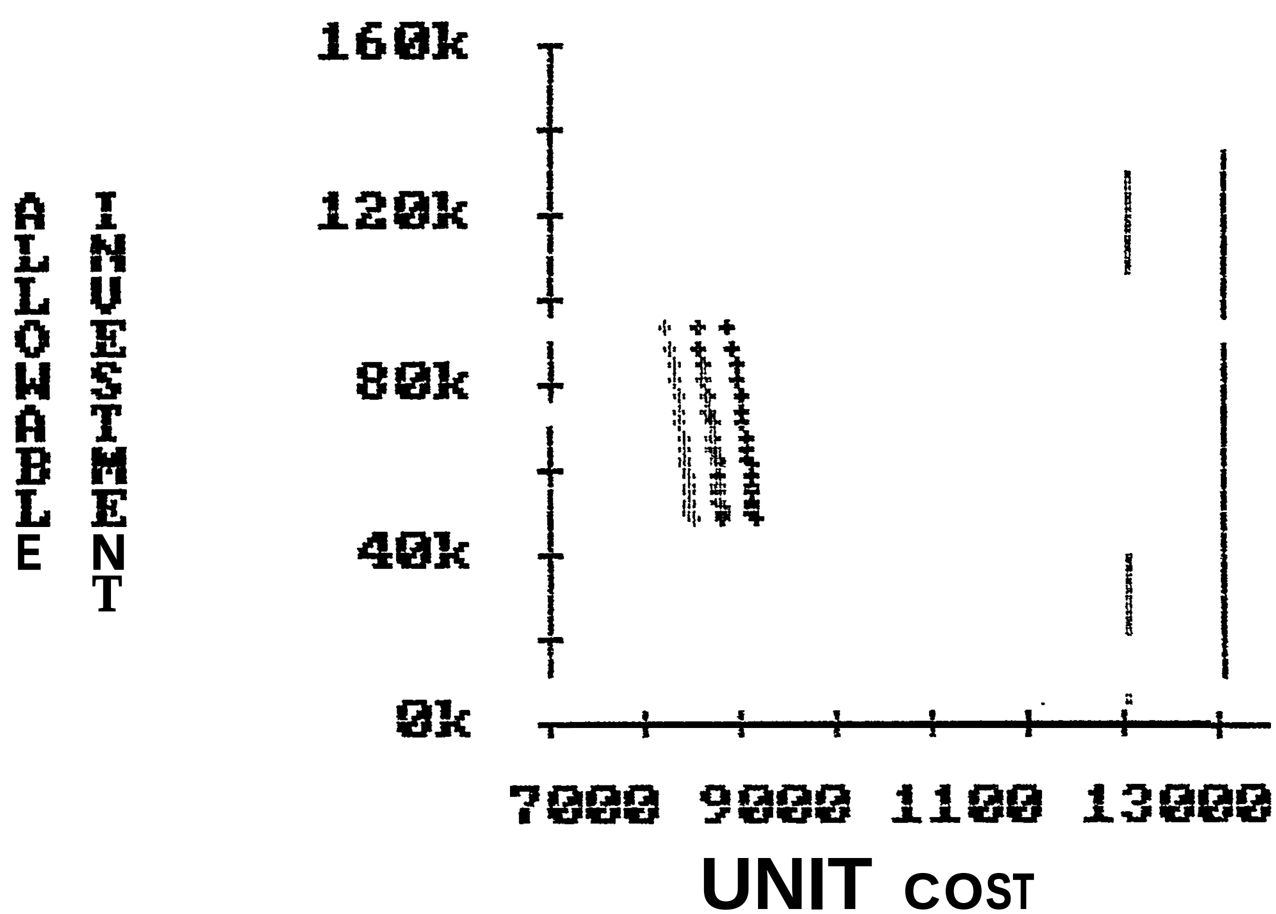


Figure 10 (b)

24 UNITS LEVEL 2 (ON BLOCKS)

MANUFACTURING COSTS 02-19-1986

240	WORKING DAYS PER YEAR
1. 0	SHIFTS AVAILABLE
0.0%	% ANNUAL INCREASE IN PRODUCTION
8. 0%	% ANNUAL COST INCREASE
3	YEAR RECOVERY OF CAPITAL EXPENSES
45. 0	% OF TOTAL COST IS DEPRECIABLE
0.0	% TAX RATE IN YEAR 0 FOR EXPENSED INVESTMENT

COMPETING SYSTEM SPECIFICATIONS

	BASE	ALTERNATIVE
WORKERS REQUIRED PER SHIFT	25.0	25.0
AVERAGE LOADED LAB0R RATE ($/HR)	30.00	30.00
OPERATING/MAINTENANCE RATE ($/HR)	20.00	20.00
ACTUAL SYSTEM CYCLE TIME (SEC)	43332.0	8961.0
MATER1AL COST ($/UNIT)	2000.00	2000.00
EXPECTED MATERIAL REJECT RATE	0. 0%	0.0%
YEARLY SPACE ALLOCATION COST ($)	0	0
YEARLY INSTITUTIONAL COST ($)	0	0
ANNUALIZED FIXED COST ($)	5000	?
YEAR 1 VARIABLE COST ($/UNIT)	9311.011	1916.658
FIXED COST ($/UNIT)	208.333	?
MATERIAL COST ($/UNIT)	2000.000	2000.00
TOTAL	11519.344	
YEAR 2 VARIABLE COST (%/UNIT)	10055.892	2069.991
FIXED COST ($/UNIT)	208.333	?
MATERIAL COST ($/UNIT)	2160.000	2160.000
TOTAL	12424.225	
YEAR 3 VARIABLE COST ($/UNIT)	10860.363	2235.590
FIXED COST ($/UNIT)	208.333	?
MATERIAL COST ($/UNIT)	2332.800	2332.800
TOTAL	13401.496	

1 YEAR NET COST SAVINGS REQUIRED

CASH FLOW PARAMETERS

YEAR	UNITS	SAVINGS	DEPRECIATION	TAX RATE	TAX CREDIT
1	24	177464	15. 00%	42.0%	8. 0%
2	24	191662	22.00%	42. 0%	
3	24	206995	21.00%	42. 0%	
3*	SALVAGE VALUE		42. 00%		

Figure 11(a)

ALTERNATIVE SYSTEM - UNIT COST

RATE OF RETURN	ALLOWABLE INVESTMENT	APPROX. PAYBACK	ANNUAL COST	YEAR 1 24	YEAR 2 24	YEAR 3 24
10%	374863	2.90	103172	8215.501	8528.834	8867.233
12%	356238	2.78	103980	8249.141	8562.473	8900.873
14%	339225	2.67	104693	8278.869	8592.201	8930.602
16%	323629	2.57	105325	8305.203	8618.535	8956.936
18%	309286	2.47	105886	8328.568	8641.901	8980.301
20%	296054	2.38	106384	8349.339	8662.672	9001.071
22%	283814	2.30	106828	8367.822	8681.156	9019.555
24%	272460	2.23	107223	8384.288	8697.621	9036.021
26%	261904	2.15	107575	8398.966	8712.299	9050.698
28%	252067	2.09	107890	8412.055	8725.389	9063.787
30%	242880	2.02	108170	8423.731	8737.065	9075.463
32%	234283	1.96	108420	8434.144	8747.477	9085.876
34%	226223	1.90	108642	8443.424	8756.758	9095.156
36%	218652	1.85	108841	8451.691	8765.025	9103.424
38%	211530	1.79	109017	8459.049	8772.383	9110.781
40%	204819	1.74	109174	8465.586	8778.918	9117.318
42%	198486	1.69	109313	8471.381	8784.715	9123.113
44%	192500	1.65	109436	8476.510	8789.842	9128.242

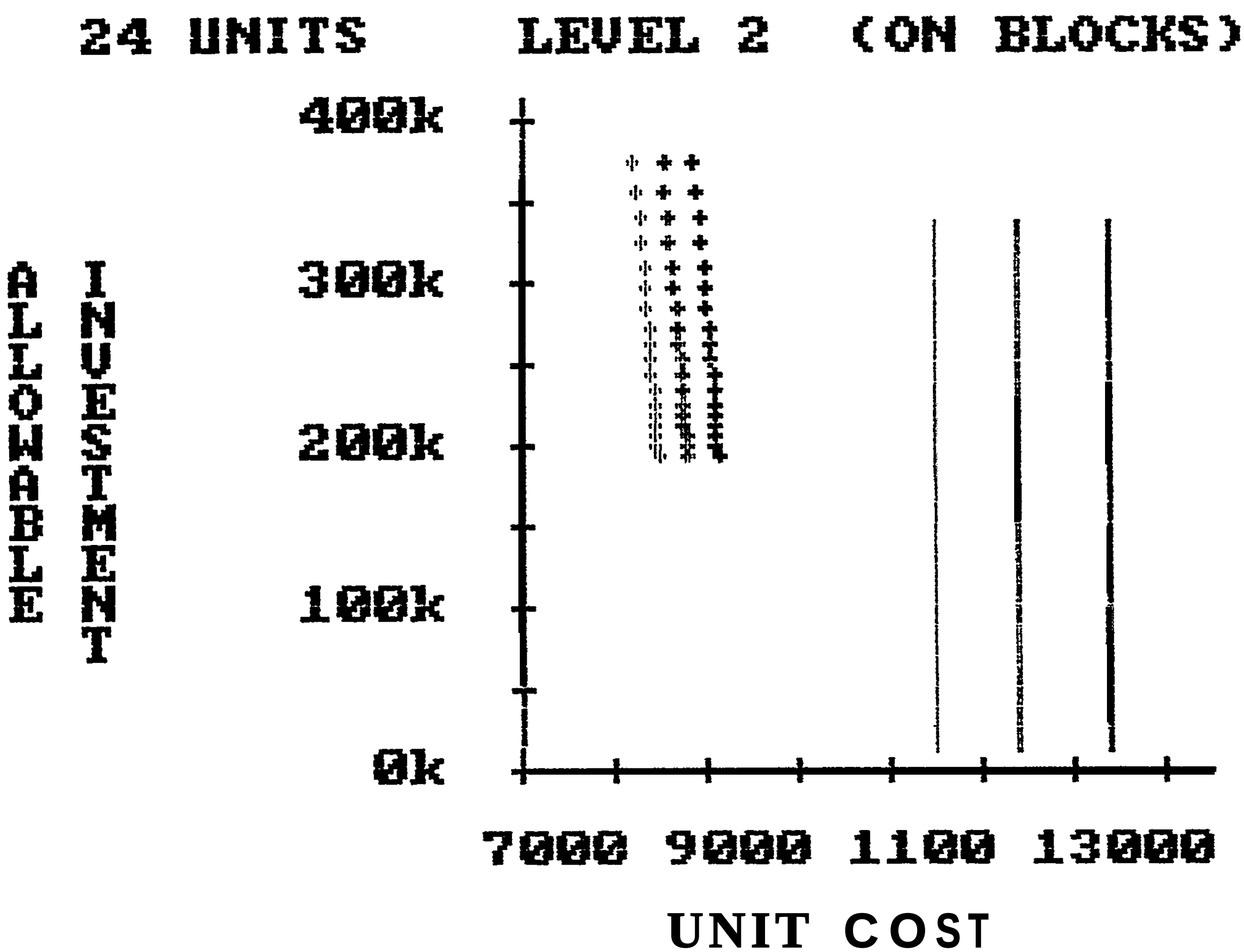


Figure 11 (b)

XII. CATEGORIZATION OF POSSIBLE SP-1O PROJECTS

The following pages present, in tabular form, a set of possible SP-10 projects that emerge directly from the foregoing chapters. The tables are organized to show main shipyard activities or main ship components, together with the important decisions and decision-makers. The projects that follow are designed to impact the decisions when that is relevant, or to improve a basic problem that was identified elsewhere in this report.

Ahead of the tables are four diagrams that indicate the logic of a strategy. Figure XII.1 repeats Figure I.2 and shows the overall implementation strategy. This strategy emphasizes combining basic knowledge, requirements analysis, novel methods, measurement techniques, and selection criteria into specifications for automation that serves an identified interim product or "problem area." Figures XII.2, XII.3, and XII.4 adapt this strategy for the specific areas of outfitting, pipe manufacture and installation, and vent fabrication and installation. Activities in dashed line boxes are either already being done by other SPC panels or are shown in solid lines on another figure in this group.

It is hoped that these tables and diagrams will be useful as presentation materials as part of project justifications. As Flexible Automation in shipyards matures, it can be expected that these figures and tables will be modified and expanded to represent additional knowledge and sophistication.

OVERALL FLEXIBLE AUTOMATION LOGIC

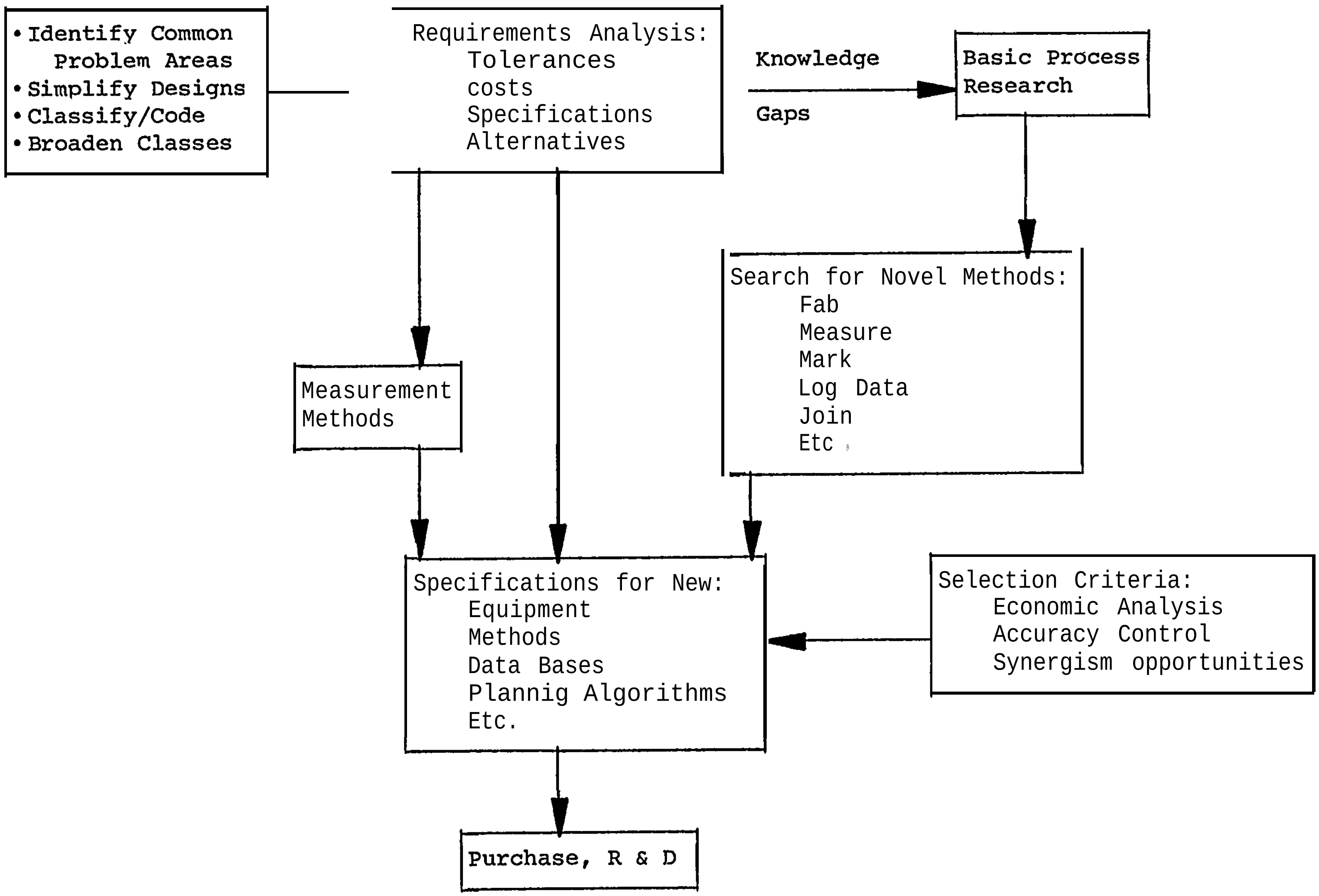


Figure XII.1: The Logic of the Implementation Strategy for Flexible Automation

FLEXIBLE AUTOMATION IN ZONE CONSTRUCTION AND OUTFITTING

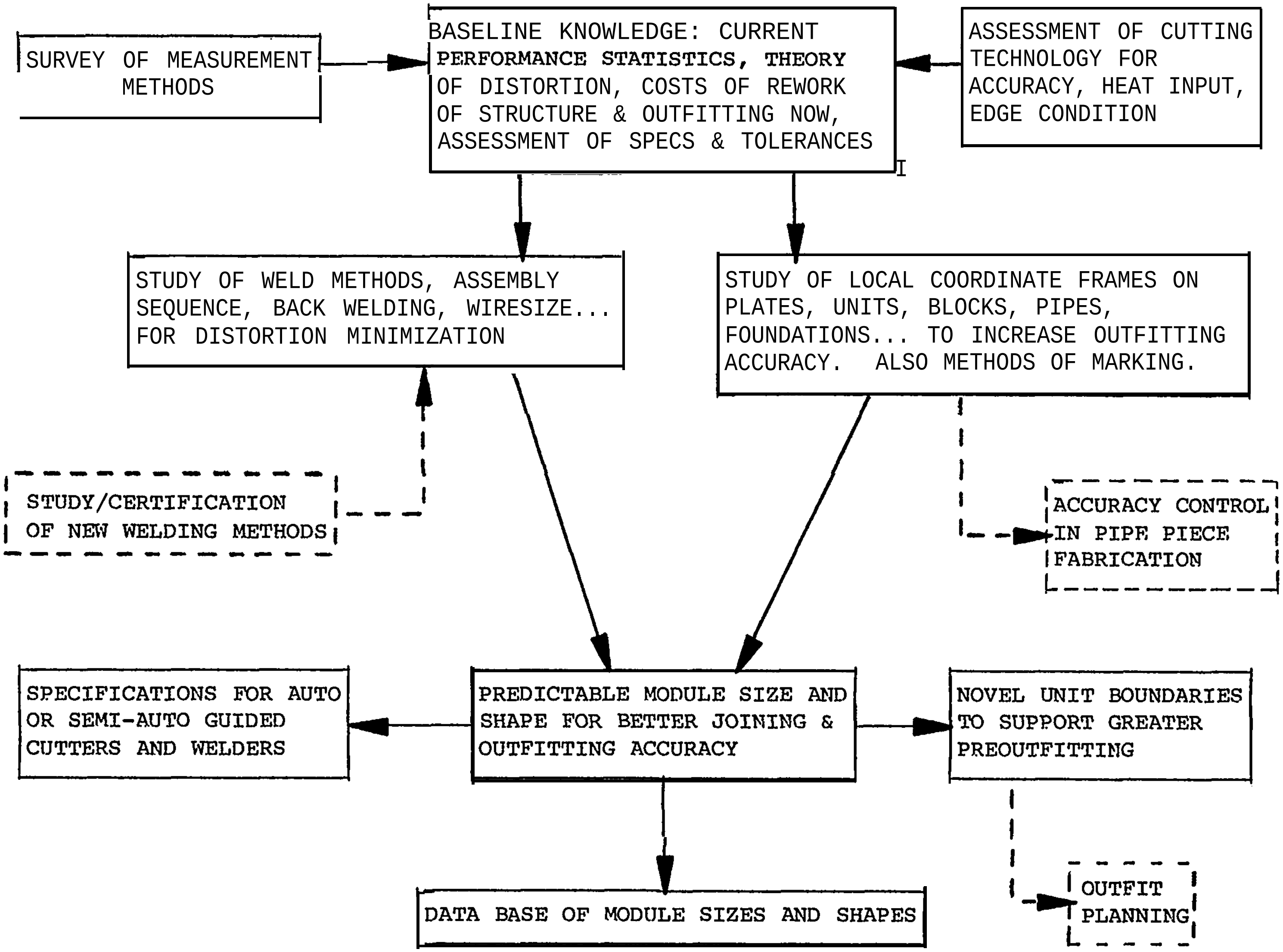


Figure XII.2

FLEXIBLE AUTOMATION IN PIPE PIECE MANUFACTURE AND INSTALLATION

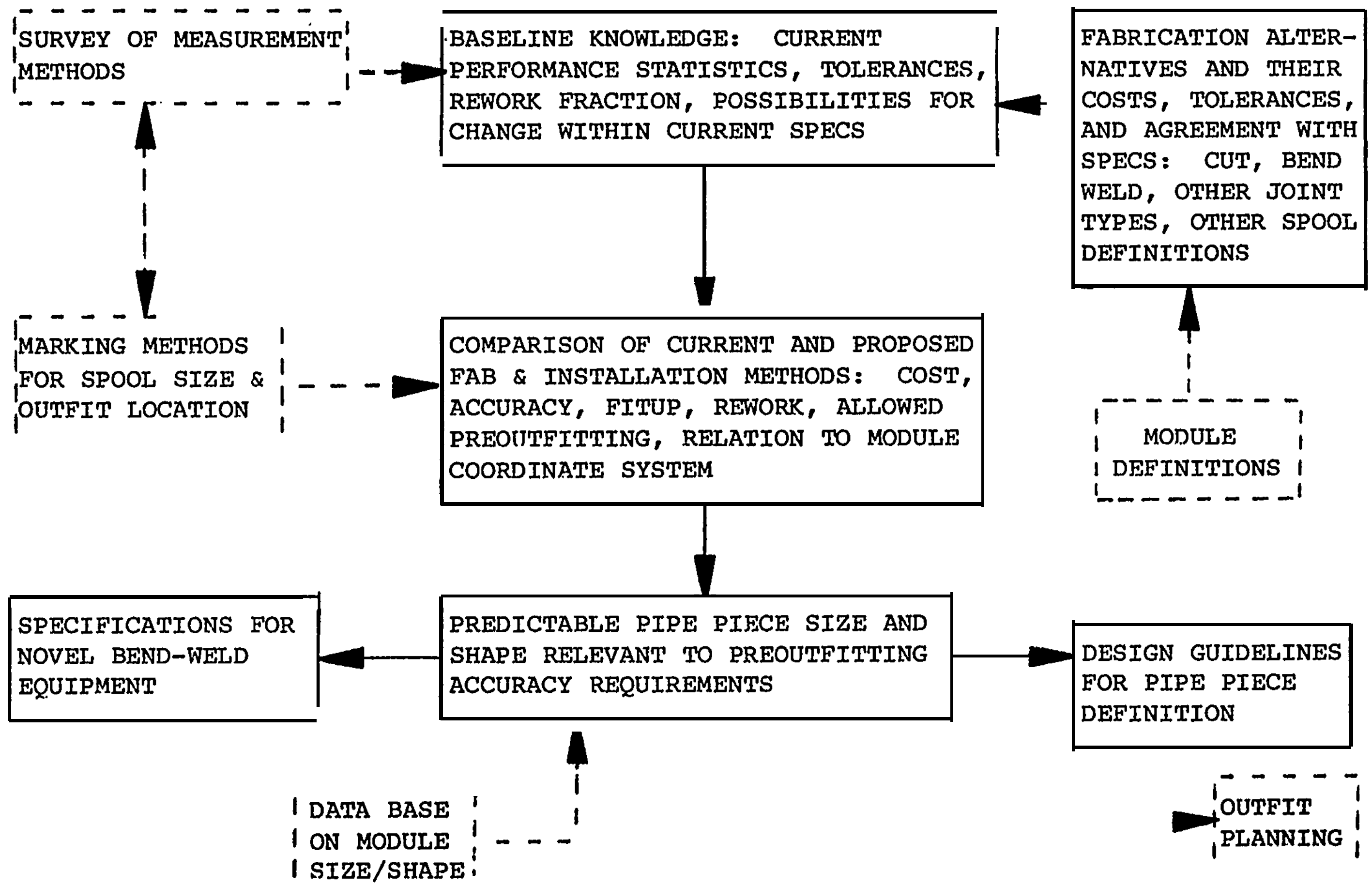


Figure XII.3

FLEXIBLE AUTOMATION IN VENTILATION DUCT MANUFACTURE AND INSTALLATION

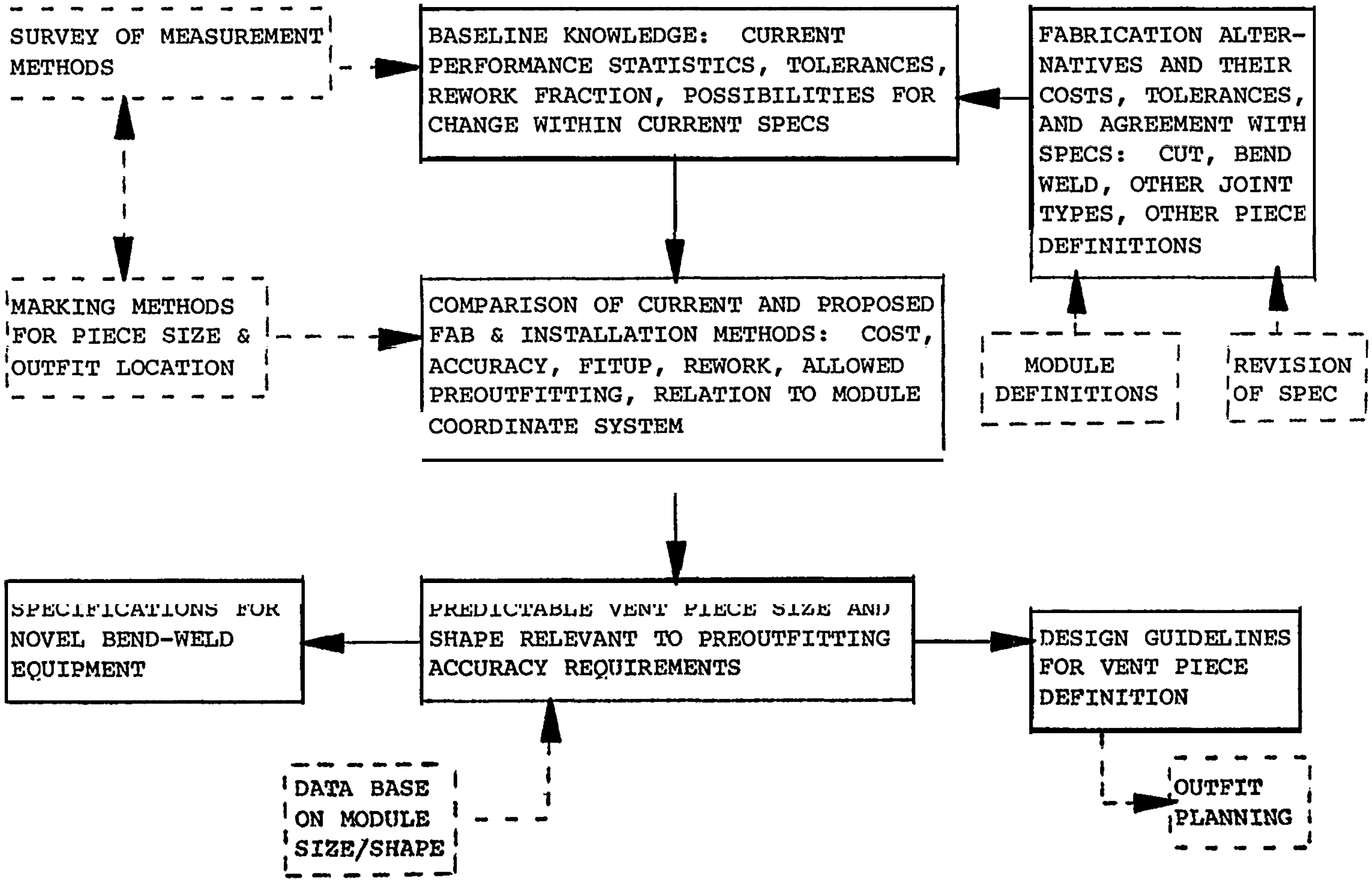


Figure XII. 4

TABLES OF IMPORTANT DESIGN - PRODUCIBILITY ISSUES, FACTORS, DECISIONS, DECISION-MAKERS, AND POSSIBLE SP-10 OR SP-X PROJECTS

MAJOR STRUCTURE

MAIN FACTORS	MAIN DECISIONS	DESIGNED BY	POSSIBLE PROJECTS FOR SP-10
MISSION, WEAPONS SYSTEMS, SPEED, ENDURANCE	SHIP SIZE, DISPL., SPEED, CREW SIZE, "TIGHTNESS", MAIN PROPULSION	NAVSEA/CNO	NONE SP-4:''TIGHTNESS" TRADEOFFS?
STRUCTURAL STRENGTH: BENDING BUCKLING	L,W,D PLATE THICKNESS, MATERIALS, FRAME SPACING & SIZE	NAVSEA PLUS YARD INPUTS	WELDING & CUTTING METHODS & THEIR EFFECT ON DISTORTION - INCLUDES SEQUENCE, WIRE SIZE, SPEED, AUTOMATION
STRUCTURAL CONSTRUCTION SEQUENCE, INCL CRANE CAPACITY	MODULE BREAKS, IDENTIFICATION OF MAIN STRENGTH MEMBERS - - - - - - - - - - PRIME FIRST VS. BLAST FIRST	DESIGN AGENT & YARD - - - - - - - - - - PLANNED BY YARD BASED ON FACILITIES & WELD-PRIME ISSUE	• ASSEMBLY SEQUENCES TO MINIMIZE DISTORTION • DEFINITION OPTIONS FOR MODULES TO AID OUTFITTING • CLEAR UP WELD-PRIME ISSUE & MAKE TIME-COST COMPARISONS

Table XII.1

MAJOR STRUCTURE CONT.

MAIN FACTORS	MAIN DECISIONS	DESIGNED BY	POSSIBLE PROJECTS FOR SP - 10
CONSTRUCTION ACCURACY	CUT NEAT VS. LEAVE EXCESS PLATE TO EGG-CRATE VS. FRAMES TO PLATE ON PIN JIGS OR DIAPHRAGMS STRATEGIES FOR BUILDING MODULES SO THAT THEY COME OUT RIGHT	YARD PLUS DESIGN AGENT INPUT	• GENERAL ATTACK ON MEASUREMENT METHODS: INSTRUMENTS, STATION POINTS ON PIERS AND ON PLATES/UNITS TO AID CONSTRUCTION AND OUTFITTING: LOCAL COORDINATE FRAME FOR EACH MODULE • CREATE NECESSARY DATA BASES • CREATE MEASURE-CUT SYSTEMS USING LASERS OR SOMETHING SIMILAR • BROADER LOOK AT HEAT-STRAIGHTENING VS. TOLERANCES, BETTER WELD SEQUENCES, ALTERNATE MEANS TO ALIGN PARTS • COORDINATED STUDY OF ACCURACY CONTROL, ASSY SEQUENCES, AND MEASUREMENT/CUT TECHNIQUES AS SYSTEM • SPECS & REQUIREMENTS STUDY ON MAJOR JOINING & CUTTING TASKS LEADING TO SPECS FOR EQUIPMENT FOR SAME. IDENTIFY GENERIC TASKS, SEEK COMMONALITY.

Table XII.1 (cont)

M I N O R   S T R U C T U R E

ITEM & FACTORS	MAIN DECISIONS	DESIGNED BY	POSSIBLE SP-10 PROJECTS
FOUNDATIONS: SIZE, LOCATION, EQUIPMENT INTERFACE, BACKUP STRUCTURE	STANDARDIZATION DETAILED DESIGN	DESIGN AGENT	IDENTIFY GENERIC TYPES & CREATE VARIANT DESIGNS FOR THEM. THEN DO ECONOMIC ANALYSIS FOR SEMI-AUTOMATIC FAB & ASSY VS. MANUAL OR AUTOMATIC
STRESS CONCENTRATIONS AND LOCAL FAILURES	DEFINITION OF STRUCTURAL DETAILS	DESIGN AGENT, NAVSEA, ABS???	• CLARIFY FUNCTION OF DETAILS FOR PURPOSE OF ELIMINATION, SIMPLIFICATION, OR REDESIGN FOR EASIER ASSEMBLY • SSC: DEFINE EXPERIMENTS AND FAILURE HISTORY STUDY TO AID FUNCTION STUDY - BE SURE DETAILS ARE BEING USED PRODUCTIVELY.

Table XII.1 (cont)

COMPONENTS - FABRICATION AND/OR INSTALLATION

ITEM & FACTORS	MAIN DECISIONS	DESIGNED BY	POSSIBLE SP-10 PROJECTS
PIPE: DELIVERY & CONNECTIVITY	PATH, JOINT & BEND LOCATION, JOINT TYPE	DESIGN AGENT & YARD	•STUDY TOLERANCES, COSTS OF FAB & INSTALLATION & MIL STD'S FOR JOINT TYPES TO DECIDE MOST ECONOMICAL: ARE SLEEVE JOINTS BETTER? •STUDY REQUIREMENTS & SURVEY TECHNOLOGY IN PIPE WELDERS AND BENDERS W/AIM OF FACILITY UPGRADES. INCLUDE COST/TIME STUDY OF EXISTING METHODS.
PIPE: SHOCK RESISTANCE	LOCATION OF HANGERS	DESIGN AGENT W/NAVSEA INPUT?	CLARIFY HANGER TYPES & OPTIONS. UTILIZE BETTER MEASUREMENTS TO GET MORE USE FROM HANGERS & AVOID OVERDESIGN.
PIPE: STRESS RESISTANCE (FOR SUBS ONLY)	LOCATION OF EXTRA BENDS, CHOICE OF JOINT TYPE	DESIGN AGENT W/NAVSEA INPUT	•SP?: NEED BETTER CAD FOR INTEGRATING PIPE CONNECTIVITY, STRESS ANALYSIS, SHOCK ANALYSIS, HANGER LOCATION, ETC. • SP-10: SINCE POOR FITUP CAUSES HIGHER STRESSES, OTHER TOPICS ON THIS PAGE WILL HELP HERE.

Table XII.1 (cont)

COMPONENTS - FABRICATION AND/OR INSTALLATION (CONT.)

ITEM & FACTORS	MAIN DECISIONS	DESIGNED BY	POSSIBLE SP-10 PROJECTS
PIPE: SHOP FAB	TOLERANCES , JIGGING METHODS , MEASUREMENT METHODS, SPOOL BOUNDARIES	YARD	STUDY SPOOL DEFINITION TO SEE HOW TO GET LONGER ONES (MORE SHOP JOINTS, FEWER SHIP JOINTS) OR SIMPLER ONES (DISTRIBUTION OF BENDS & FITTINGS). CONSIDER WELD/BEND SEQUENCES, AVAILABLE TECHNOLOGY, AND TOLERANCE CONTROL STUDY NOVEL METHODS OF INTEGRATING SHOP JIGGING WITH MEASUREMENT METHODS. MUST PROVIDE CONVENIENT MEASUREMENT DATA FROM DESIGN
PIPE: SHIP INSTALLATION	SEQUENCE, TOLERANCES, JOINT TYPE, MAKEUP TO NEXT MODULE	YARD	INTEGRATE WITH MODULE MEASUREMENT & DEFINITION PROJECTS TO ESTABLISH OUTFIT COORDINATE SYSTEM. SOME PIPES CUT NEAT, SOME WITH EXCESS ACCORDING TO RATIONAL STRATEGY.

Table X11.1 (cont)

COMPONENTS - FABRICATION AND/OR **INSTALLATION (CONT.)**

ITEMS & FACTORS	MAIN DECISIONS	DESIGNED BY	POSSIBLE SP-10 PROJECTS
MACHINERY: FOUNDATIONS , ADJACENT STRUCTURE, PIPE RUNS, LIFE CYCLE COST	LOCATION,WEIGHT BALANCE, FUNCTIONAL GROUPS	NAVSEA WITH LIMITED YARD & DESIGN AGENT INPUT	OPTIMIZATION SOFTWARE TO SUGGEST BETTER GROUPINGS: SHORTER OR STRAIGHTER PIPE RUNS, PRE-OUTFITTED GROUPS, UNITIZED FOUNDATIONS, WOULD RESULT. THIS IS RELATED TO PIPE DELIVERY/CONNECTIVITY, SINCE TWO CLASSES OF RUNS (LOCAL AND REMOTE) CAN BE DEFINED AND EXPLOITED TO SIMPLIFY DESIGN, CONSTRUCTION, CREW TRAINING, REPAIR, ETC. SAME THING HAS ALREADY HAPPENED IN ELECTRONICS.
VENT : CONNECTIVITY , DELIVERY, CROWDING, NOISE	CENTRALIZED VS. DISTRIBUTED FAN, HEAT, AND COOLING FACILITIES, PATHS, SHAPES, JOINT LOCATIONS	NAVSEA & DESIGN AGENT	SIMILAR TO ABOVE PROJECT FOR PIPE, BUT EVALUATE BENEFITS OF DECENTRALIZING: LESS CROWDED FAN ROOMS, SIMPLER VENT DUCT. CURRENTLY DUCT IS TOO INTRICATE, PIECES ARE TOO SMALL, LINE LOSSES MAY BE TOO BIG.
VENT: CONSTRUCTION METHODS	JOINT TYPE, FAB STRATEGY, CERTIFICATION FOR WT OR DP, JOINT LOCATIONS	NAVSEA SPECS, DESIGN AGENT DETAILS	STUDY NOVEL FAB METHODS DERIVED FROM ORIGAMI OR OTHER TECHNIQUES. EXPLOIT ABILITY TO NC CUT ANY SHAPE ACCURATELY. BENEFIT IS FASTER FAB, FEWER JOINTS. PUSH ONGOING STUDIES OF WAYS TO IMPROVE SIMPLE FAB TECHNIQUES TO QUALIFY THEM AS DP OR WT: JOINT SEALANT, INSIDE COATINGS, OUTSIDE COATINGS.

Table XII.1 (cont)

O U T F I T T I N G

MAIN FACTORS	MAIN DECISIONS	DESIGNED BY	POSSIBLE PROJECTS FOR SP-10
PLANNING	DESIGN FOR ACCESS (MACHINERY, PIPE, VENT, WIREWAYS)	DESIGN AGENT W/ YARD INPUT	• SURVEY EXISTING METHODS IN ARCHITECTURE, CONSTRUCTION PLANNING, SEARCH ALGORITHMS, ARTIFICIAL INTELLIGENCE, SHOP SCHEDULING, 3D MODELING, COMPUTER ANIMATION.
	TIMING & SCHEDULING	YARD	STUDY DIFFERENT ORGANIZATIONS/ MANAGEMENT TECHNIQUES - "OUTFIT TEAMS," FOR EXAMPLE.
TRANSPORT & DELIVERY OF ITEMS TO MODULES	WHEN TO INSTALL IN BUILD SEQUENCE VS. MODULE JOINING	YARD	N0VEL LIFT & CARY DEVICES (MUST RELATE TO MODULE DEFINITION PROJECT) IMPROVE DATA BASES SO THAT PART-TOOL KIT LISTS CAN BE CREATED FOR EACH JOB
LOCATION ACCURACY OF RIGID ITEMS	HOW TO SPECIFY LOCATION MEASUREMENTS , FIXED AND FREE ENDS, NEAT AND RICH ENDS, ETC.	YARD & DESIGN AGENT, IF ANY	ANOTHER ASPECT OF THE MEASUREMENT PROJECT UNDER "MAJOR STRUCTURE." MUST INCLUDE MARKING METHODS AND INSTALLATION - SPECIFIC DATA ON DRAWINGS.

Table XII.1 (cont)

XIII. FUTURE WORK AND OPEN QUESTIONS

A. Broad Questions

1. Design Rationalization

According to several authorities(l), ship design contains too many approximations and simplified analyses, backed up by too few experiments. This, combined with uncertainty about conditions ships will face, makes designers reluctant to consider design changes to aid producibility. As long as this situation persists, shipbuilding will be denied the best proven cost reduction method used in manufacturing, namely product redesign. A directed program of prioritized proposed changes, accompanied by verification tests, could address this problem. Leadership will have to come from naval architects who have been sensitized to producibility issues.

2. The Tightness Tradeoff

Many pressures combine to produce the customer's specifications for a ship. In case of Navy ships, the desire to have maximum capability at low cost tends to create a ship packed with equipment, a "tight ship." Considering life cycle costs, a "loose" ship may be costly, since a large hull would be carrying relatively little capability. But a tight ship may be costly, too. Being crowded, it is harder to build: short pipe and vent pieces, complex shapes and many joints, all installed under inefficient conditions, have been discussed above. But operating and repairing a tight ship are costly, too, for the same reasons. Replacements for contorted pieces will also be contorted. This tightness tradeoff has been much discussed, but little is known about whether current ship designs are too loose, too tight, or in the middle. To the extent that they are too tight, piecepart fabrication is too costly and outfitting is too inefficient as a result.

3. Cost Estimating in Early Design

Estimating the basic construction cost of a ship is difficult. There are too few data, time standards, or design standards to permit good prediction. In addition, too much time is unproductive, wasted by outfitting inefficiencies or poor shop organization. What a job does cost may be known at some level, but what it should cost is not. In response to this, much early cost estimating is crude, based on weight estimates or weld length count or synthetic area of plate.(1) paradoxically, a result of this is that a tight ship, being lighter, is predicted to cost less.(2)

4. Design Elegance Tradeoffs

Compared with 40 years ago, today's combat ships have thinner shells and denser framing. This reflects development of design knowledge and higher strength steels. But it has several adverse effects on producibility: denser framing increases the number of intersections and structural details, and thin plate common to today's ships is more subject to heat distortion during welding than either thicker or thinner plate.(3)

5. Knowledge Gaps in Process and Outfit Planning

Japanese prowess in preoutfitting is well-known, but combat ships present unique outfitting problems. This is clear from cost analyses of Japanese cargo ships(4), where structural work dominates. Yet in structural work alone, the Japanese are anecdotally quoted as being about 3 times more efficient in man-hours than U.S. yards. So, while improvements can be expected in structure, it is not clear how much improvement will occur in pipe, electrical, and equipment outfitting. There is a need for better planning methods. Currently, group discussions are the only method used.

6. Design Impacts and Yard Facilities

On the recent DDG-51 design program, the Navy considered assigning module boundaries that would govern block construction. Boundary location affects equipment location, tolerances, and, especially, module weight. Since some yards have more crane lift capacity than others, some designs clearly favored some yards over others. To avoid biasing the upcoming bidding, boundary locations were omitted from the contract design, although equipment locations had to be assigned. A less producible design may result.

7. Industry Rationalization

The variation in facilities between yards is clearly detrimental to the Navy, since it must reduce the producibility of the design to the lowest common denominator. Some yards cannot use the best methods or outfit the units as fully because full units are too heavy or the yard is too small. Two strategy options come to mind. The Navy could consider the current imbalance as anticompetitive, and could provide funds to facilitize an equalization. Or the yards could adopt a longer range strategic plan and position themselves to bid more competitively. Normal cost accounting methods cannot be used to justify such a decision, since it involves deciding whether to stay in the business or not.

B. Detailed Questions

1. Structural Process Standards

It has been of great interest to us to see how different yards do the same jobs. Some yards weld stiffeners to plate, while others make egg boxes of stiffeners and then put the plate on. Some yards build up large units and blast them all at once while others build smaller units and begin outfitting them almost immediately, doing only touchup blasting. Some yards use one side welding while others do not. In many cases the same class of ship is being built. Each of these choices has great impact on cost, structural accuracy, outfit efficiency, or other issues. What systematic studies have been done to expose the pros and cons of these alternatives?

2. What Accuracy is Really Possible in Structure and Pipe?

A priori and based on temperature considerations, it appears that achieving 0.25 inch errors in large structures means doing rather well, but not well enough to avoid rework. It is clear that the Japanese are doing more than just measuring. One can imagine measuring partly finished assemblies and altering the plans of subsequent pieces on line so that the last piece compensates for the remaining errors. Would this be worthwhile?

What data transmission and processing capabilities would be needed? Or can careful planning of weld sequences and monitoring or control of temperature reduce errors to 0.125 inch?

Is there an optimum size for a unit, where too small does not allow for enough preoutfitting and too big requires too much cutting and awkward outfitting? The Japanese experience may not give any guidance here, given the differences between commercial and combat ships.

3. Totally New Methods in Pipe and vent

It would seem that in many vent and pipe systems where pressures and temperatures are not extreme, lower cost methods or materials could be used. The fabrication of complex pipe and vent pieces is very expensive (typically 5 to 8 man-hours per pipe spool or 50000 to 80000 man-hours per FFG for pipe over 1.5 inches diameter). While alternate materials might be less damage resistant, they might also be much easier to repair. What detailed studies have been done here?

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4. Sasano, R., "Robotization in Shipbuilding Industry," Proceedings, 2nd ISRR, Kyoto, Japan, MIT Press, 1985.

XIV. CONCLUSIONS AND RECOMMENDATIONS

A. General Conclusions Concerning Flexible Automation

1. Flexible automation is any automation technology that can be reconfigured to be able to process variations of the same type of work. The opportunities for automation in fabrication depend heavily on other activities such as planning, design, scheduling, measuring, and tolerancing, to name a few. Automation of part or all of these non-fabrication activities too is desirable and necessary because no single island of automation can have the effect of a unified and broad approach.

2. The need for cost reduction, better process control, more efficient operations, more rationalized designs, and new processing techniques will increase in both civilian and military shipbuilding.

3. The benefits of flexible automation will extend to both civilian and military, public and private, yards.

4. No one technology, device or machine characterizes or comprises flexible automation. In particular, further study of the type recommended below will show that current industrial robots are inappropriate for most shipyard work because they are too heavy or do not have the correct reach, load capacity, or controls. Instead of robots alone, flexible automation of the future will comprise reconfigurable machines built to specifications generated by shipyards and outside engineering firms as a result of careful study of individual types of operations. Such studies will reveal the necessary specifications for such equipment.

5. Successful flexible automation requires a suitable environment comprising:

a) good understanding of the processes to be automated

b) rational design of the workpieces, including standardized and simplified shapes and appropriate tolerances

c) rational design of work packages to increase the number of parts or assemblies suitable for one workstation ***or*** process lane

d) measurement methods capable of verifying the required tolerances

e) time and cost standards for work, plus methods for measuring performance

f) educated yard personnel sensitive to measurement, tolerances, data taking, statistical methods, and process improvement

6. Competitive shipbuilding is an intensely scientific enterprise, relying heavily on careful planning, rationalization of work, quantitative performance monitoring, and the ability to predict the technical and economic outcome of each work step. Flexible automation will enhance this characteristic of shipbuilding by requiring improved process understanding and by providing the opportunity to measure and monitor the processes. The equipment, if properly designed, will include the ability to be reprogrammed to absorb improved process knowledge and better methods as they are created through data and performance analysis.

7. Flexible automation will provide the following benefits:

a) reduction of direct labor and improved safety

b) reduction in job completion time

c) improved predictability of work output in terms of time and tolerances

d) reduction of rework due to improved workpiece uniformity and accuracy

8. Flexible automation is an interdisciplinary activity and as such will require cooperation and interaction between many

departments of a shipYard as well as between several panels of the Ship Production Committee. Yard departments with major inputs include Planning (master build schedule, module and unit definition, outfit planning), detail design and planning (module definition, equipment location, tolerance planning, workpiece standardization and simplification) and industrial and manufacturing engineering (methods planning, data gathering and analysis, process improvement, work package definition). In the SPC'S panels have major contributions to make.

B. Status of Shipbuilding and Its Level of Automation

9. Automation in shipyards today is limited to design and early processing of single workpieces. There is extensive CAD in use and even more commercially available. Much automation is in use for cutting out single pieces. By contrast, there is much less automation in use for changing the shape of pieces or for joining them, although in some cases there is commercially available equipment. There is little automation of transition design, work package definition, scheduling, outfit planning, measurement, or the systematic practice of data taking/fee~ack/process improvement.

10. Ships' fabricated components, especially structure and sheet metal, are designed to be built up from elementary raw stock, with emphasis on separate pieces, many cuts, and many joints. This approach proliferates pieces and creates many fitting, measuring, and joining steps. It also creates chances for error and distortion. Finally, it creates designs that are difficult to automate. Imagination and effort need to be devoted to finding new approaches that require fewer cuts and joints, or which unify steps that are currently distinct. In manufacturing, such approaches lead more easily to automation, more uniform work, and higher quality.

11. Heat-induced distortion is one of the most troublesome problems in shipbuilding. It intervenes pervasively by lengthening the time between the arrival of pieces at a workstation and completion of their assembly. When pieces are finally fitted well enough for welding, only a small proportion of the time is left to be saved by automating the welding. Priority needs to be given to developing cutting and joining methods or other aids that reduce distortion or remove it promptly.

C. Design and Production Issues that Affect Producibility and Automation

12. U.S. shipbuilding today lacks both the data and evaluation means to process the data so that automation and productivity opportunities can be systematically identified and evaluated. Cost tracking methods often capture only part of the cost and do not allocate it accurately to interim products or key steps in making them. Tolerance performance data are gathered only sporadically or only on some kinds of parts. In most cases there is a qualitative feeling that the work is “good enough.” Priority should be given to projects that enhance data gathering and analysis (tolerances, SPC, cost tracking) and to those that create new decision-making aids (scheduling, economic analyses, factor analyses).

13. We find that, as in manufacturing, much of the cost of building a ship is determined when it is designed. Unlike manufacturing, ship design is dispersed over many agencies that communicate with each other too little and who have conflicting or disjoint goals. Further, unlike manufacturing, shipbuilding contains ***a*** great deal of ongoing planning that also influences cost. While the Japanese have shown that costs can be saved by paying attention to these issues, the scientific basis for the decision-making is not strong; instead, it is heavily experience-based, making it difficult to transfer to U.S. yards.

To strengthen the science base will require deep study of process after process, item after item. Very detailed studies will be needed concerning tolerances, standards, training of designers, delineation of decision-making authority, and education methods and curricula.

14. Numerous decisions must be made about work, tolerances, standards, unit definition, and so on, before flexible automation can advance in shipyards. The power to make most of these decisions rests with yards and the detail designers. The customer and the classification society hold the key in areas related to standards, where process improvements and simplifications could be obtained, but key blockages to flexible automation do not exist in this domain. In the broader area of producibility in general, the customer holds great power, due to his ability to redefine entire technologies, configurations and specifications in structure, materials, wiring, and equipment. However, it is only after such broad decisions are made that the options for flexible automation would become clear.

15. There appears to be no formal, centralized procedure by which new ideas for producibility, fabrication techniques or materials can be evaluated and certified by the Navy, comparable to the Research Division of the ABS. There are instead highly decentralized activities which sometimes lead to inconsistencies in approved techniques and dilute efforts to introduce new methods. Yet we can expect increased activity in flexible automation to lead to challenges to current standards and to offer totally new methods as a result of increased process understanding, new materials, or innovative design concepts. A way to bring these ideas systematically to definitive test and, if approved, adoption throughout the Navy is needed.

D. General Conclusions Regarding Implementation of Flexible Automation

16. Implementation of flexible automation should be correlated and integrated with ongoing efforts to convert shipbuilding to a product-oriented basis. Product-oriented shipbuilding will improve process and module definition, cost tracking, and rationalization in general. Flexible automation should be targeted toward identified problem areas, and should be designed to handle families of pieces and interim products identified by coding and classification methods. Flexible automation, in turn, will contribute to product-oriented shipbuilding by offering predictable quality levels, and cost-time-tolerance data for management data bases.

17. Any implementation plan must contain these elements:

- a targeting mechanism to identify opportunities
- a means of realizing proposed automation ideas
- a way of evaluating potential and actual benefits, both economic and technical

18. Possible targeting mechanisms include identifying:

- dangerous, strenuous, and/or repetitive jobs
- similar work problems (this assumes that there are efforts to redefine workpieces, subassemblies, processes tolerances, etc., to expand the scope of easy problem areas and reduce the scope of difficult ones)
- processes that have demonstrated, via SPC techniques, that they are under control
- processes that have been identified by SPC as having residual variations (X-bar or "R") that are unacceptably large
- processes that are costly to perform manually or which are costly to follow UP due to the rework they create

- part types or processes where automation could improve the likelihood of passing inspection, having longer life cycle, or meeting strength, shock, or other specifications
- opportunities for indirect economic benefit, including reduction of loss, damage, or delay
- fabrication or joining operations where automation would raise quality or tolerances so that the automation of subsequent steps would become feasible

E. Specific Implementation Steps

19. Implementation of flexible automation and of single automation projects should follow this general sequence:

a) the process to be automated must be studied and modeled so that its output is predictable given the controllable inputs

b) the requirements for the process must be rationalized

c) measurement methods must be found or created to monitor the process while it is ongoing and after it finishes

d) existing technology and methods from other fields must be surveyed to determine what is already available or can be modified to suit the shipyard problem

e) designs and work packages must be studied to reveal groups sharing essential characteristics which can be encompassed by one machine or processing center, and to identify the variations within the group that the equipment must accommodate by its flexibility

f) a working scenario must be created for the equipment, comprising how it and the work are to meet physically, how reference dimensions are to be communicated and established, how the work is to be done, and how its performance is to be measured, reported, and improved

g) given this knowledge, the specifications for the equipment must be drawn up, comprising size, weight, motions, activity, worker roles, times and costs

h) if the above studies reveal gaps in knowledge or lack of equipment that can do the required work, then research or development tasks must be defined to fill those gaps.

20. Initial flexible automation projects should be chosen in areas where technology exists now. Such areas include structural and sheet metal welding and shape changing, pipe fabrication and joining, piecepart cutting and marking, and measurement. In defining these projects, use should be made of the skill and experience of yard employees, and knowledge and results from other SPC panels should be incorporated. The role of yard employees in any resulting systems or equipment should be defined from the start, and they should be involved in the definition. These projects need not contain technological leaps in order to be effective. Instead, priority should be given to simplicity, effectiveness, and the certainty and obviousness of their success.

21. These initial projects should be used for two purposes over and above the basic one: to learn about flexible automation technology in a "safe" environment, and to identify gaps in knowledge about processes, shortcomings in available technology, and lack of skills or knowledge among yard personnel. These gaps should be communicated to the customer, the classification societies, other SPC panels, other committees of SNAME such as the Ship Structure Committee, and to researchers in industrial processes and naval architecture.

22. At the same time as relatively safe initial projects are defined, research projects should be started in areas where there is little or no existing technology, or where the knowledge base is weak. These include systems where automatic measure-learn-improve cycles would be implemented, or where totally different fabrication methods would be employed, typically in pipe, vent, or electrical distribution systems.

23. Where study, research, or project implementation reveal the need for or advantage of altering standards or broadening them to encompass new methods, an early start should be made on evaluation and certification by the appropriate study agencies due to the time needed to ensure that new methods are suitable. The full force of the yards and the SPC must be brought to bear to demonstrate the potential advantages and to encourage evaluations to be made.

24. Specific attention should be given to projects that identify data needs, both technical and economic, and that create ways of evaluating data and pinpointing economic or technical opportunities for automation or process improvement.

F. Some Specific Target Areas

Flexible automation can fruitfully be applied in the following areas (in no particular order and not necessarily to exclude areas not mentioned):

a) management and design tasks like transition design, module or assembly definition, work content estimation, coding, planning outfit sequences, long term scheduling, short term scheduling, and shop load leveling.

b) measurement and locating points on parts, units, and large modules so that outfitting will be easier, installed items will fit the first time, or variations can be communicated to shops and parts reshaped in advance to fit.

c) fabrication tasks like distortion removal, low distortion joining methods, or cutting and edge preparation methods that meet higher tolerance standards and generally contribute to faster assembly.

d) areas where changes in specifications could reduce cost or permit automation, typically in equipment interfaces, vent, cables, and supports for distributive systems.

e) areas where changes in design could simplify structure or structural details so that integrity could be maintained but simpler shapes and fewer pieces could do the job.

G. "Mission" Recommendations

The following general missions are recommended for the Navy, the Yards, and Educators/Researchers:

Customer Missions -

1. Extend previous efforts to involve yards during concept and contract design. Too often we were told by customer design staff that they had no idea of yard fabrication methods. Without knowledge of producibility impacts, contract designers cannot contribute to lower costs and may in fact disrupt automation efforts.

2. Rethink specifications and tolerances. Changes in materials, joining and inspection methods, and increased ship complexity have run far ahead of many specs, which have not been thoroughly examined in years or decades. A promising step is an ongoing study of ventilation duct specs.

3. Create designs, standards, and funding incentives that encourage yards to rationalize shipbuilding. A negative example is the calculation of progress payments based on percent of structure completed. This formula discourages preoutfitting.

4. Establish a centralized mechanism for evaluating and approving process improvements, and certifying yards or vendors. The present situation of approving individual yards and/or individual ship classes produces inconsistent and contradictory results and interferes with creation of a critical mass of uniform methods.

Yard Missions -

1. Exert more control where they have it now, in detailed design, build strategy, planning, documentation, data gathering, analysis, and decision-making based on data. Tremendous progress is possible through zone design and construction, grouping of similar jobs, detail design simplification, and process improvement.

2. Make the most of the options allowed by existing standards. This will require questioning existing detailed design methods and habits.

3. Identify and thoroughly justify new design or fabrication options. Until or unless the customer establishes a centralized mechanism, it will be up to the yards to search others yards' or manufacturing and construction industries' methods, and learn how to adopt them.

4. Establish better cost capturing methods so that the total cost of performing jobs can be identified. In one yard, for example, only 40% of the cost of creating pipe pieces was charged to the pieces themselves.

Educator/Researcher Missions -

1. Make producibility a high priority. Too many naval architects see a ship as a thing to be designed rather than as a thing to be built and operated. The naval architecture program at the University of Michigan is addressing this problem.

2. Identify the knowledge gaps and research needs of producibility as an intellectual area. The current amount of experience should not be allowed to mask the lack of a scientific knowledge base. To appreciate the gaps, one need only note the degree to which yards differ in basic matters such as when to blast and prime structural assemblies or what shape those modules should be.

Common to the above missions are two main themes:

1. The need to get better' visibility into current practices--designs,costs, times, tolerances, errors--so that genuine knowledge gaps can be identified and rational solutions proposed, tested, and implemented.

2. The need to couple design, planning, and production together more tightly.

APPENDIX A

Analysis of a Single Level Process

Every process has three major cost centers:

1. Materials cost (M) - value-added to the point where the process starts.

2. Process cost (P) - the cost incurred for performing the process correctly.

3. Rework cost (R) - the (often undocumented) cost incurred when normal processing is interrupted (e.g. failed test, parts do not fit, machine downtime, wait time, etc.)

Since actual cost numbers are very difficult to establish, the ensuing discussion will use ratios of costs.

Suppose that a process is to produce q units or work pieces in a batch. The theoretical cost for level i would be

$$C_{T_i} = q(M_i + P_i) \tag{1}$$

or

$$C_{T_i} = q\left(\frac{M_i}{P_i} + 1\right)P_i \tag{2}$$

As mentioned earlier, it is likely that $P_3 > P_2 > P_1$ (where the subscript denotes level) and since M is the constant materials cost, we see that

$$C_{T_3} > C_{T_2} > C_{T_1} \tag{3}$$

This certainly indicates that the earlier in the process that pieces can be installed, the better.

What about the process interrupts? Each such operation (r being the number of them) causes an R activity and increases the actual q through the P activity since each item reworked must be reprocessed. The usual way of expressing such occurrences is to define a nominal yield rate. Improvement of the yield obviously reduces non process activity (rework) and therefore reduces the cost.

The actual cost for level i can be defined as

$$C_{A_i} = q\,M_i + (q + r_i)P_i + r_i R_i \tag{4}$$

or

$$C_{A_i} = \left[q\left(\frac{M_i}{P_i} + 1\right) + r_i \left(1 + \frac{R_i}{P_i}\right)\right] P_i \tag{5}$$

We can easily determine the ratio of actual cost to theoretical cost by dividing (5) by (2)

$$T_i = \left(\frac{C_A}{C_T}\right)_i = 1 + \frac{\left(1 + \frac{R_i}{P_i}\right)}{\left(1 + \frac{M_i}{P_i}\right)} \left(\frac{r_i}{q}\right) \tag{6}$$

It is apparent that as $r_i \to 0$ in (6), $T_i \to 1$. We must now establish the relationship between r_i and q.

First, we can define the usable failure rate (f) of the process. For example, when q = 4 the failures rates can be 0, 1/4, 1/2, 3/4 and 1. Zero (meaning perfect) and one (total failure) are immediately dismissed from future consideration. The f = 3/4 failure rate has mathematical interest as we shall see later but does not have a physically explainable meaning.

The remaining two f values have important characteristics, since they can be readily interpreted.

$$f_a = 1/4 = 4^{-1} = q^{-1}$$

$$f_b = 1/2 = 4^{-1/2} = q^{-1/2} \qquad (7)$$

In general we can say that the failure rate must be

$$f_n = \frac{1}{q^{(1/n)}} \qquad (8)$$

How does this determine r_i? If we assume that the nominal failure rate applies each time units are processed (failures keep occurring [n-l] times until only one unit remains), we see that

$$r_i = 1 + (f_n q) + (f_n q)^2 + (f_n q)^3 + \dots + (f_n q)^{n-1} \qquad (9)$$

or

$$r_i = \sum_{j=0}^{n-1} (f_n q)^j \qquad (10)$$

Substitution of (8) into (10) results in

$$r_i = \sum_{j=0}^{n-1} q^{(j/n)} \qquad (11)$$

Equation (11) can be expressed in more meaningful terms if we recognize that the finite geometric sum is

$$s = 1 + a + a^2 + \ldots + a^{N-1} + a^N = \frac{1 - a^{N+1}}{1 - a}$$

For the case at hand

$$a = q^{(1/n)}, \qquad N = n - 1, \qquad S = r_i$$

thus

$$r_i = \frac{1 - \left[q^{(1/n)}\right]^n}{1 - q^{(1/n)}}$$

or

$$r_i = \frac{1 - q}{1 - q^{(1/n)}} \tag{12}$$

If we rearrange (8) as

$$q^{(1/n)} = \frac{1}{f_n}$$

and substitute it into (12), we obtain

$$r_i = \frac{1 - q}{1 - 1/f_n} \tag{13}$$

We now define yield to be one minus the failure rate, or

$$y = 1 - f \tag{14}$$

Substitution of (14) into (13) and rearranging results in

$$r_i = 1 - \frac{1}{Y} \quad 1 - q \tag{15}$$

then

$$\frac{r_i}{q} = \left(1 - \frac{1}{y}\right) \left(\frac{1}{q} - 1\right) \tag{16}$$

or, to eliminate negative values

$$\frac{r_i}{q} = \left(\frac{1}{y} - 1\right) \left(1 - \frac{1}{q}\right) \tag{17}$$

We can now substitute (17) into (6) to obtain

$$\boxed{T_i = \left(\frac{C_A}{C_T}\right)_i = 1 + \left(\frac{1 + R_i/P_i}{1 + M_i/P_i}\right)\left(\frac{1}{y} - 1\right)\left(1 - \frac{1}{q}\right)} \tag{18}$$

Equation (18) can be mathematically applied for any values of the parameters. Typical output from computer program SLP is shown in Figures 1 and 2.

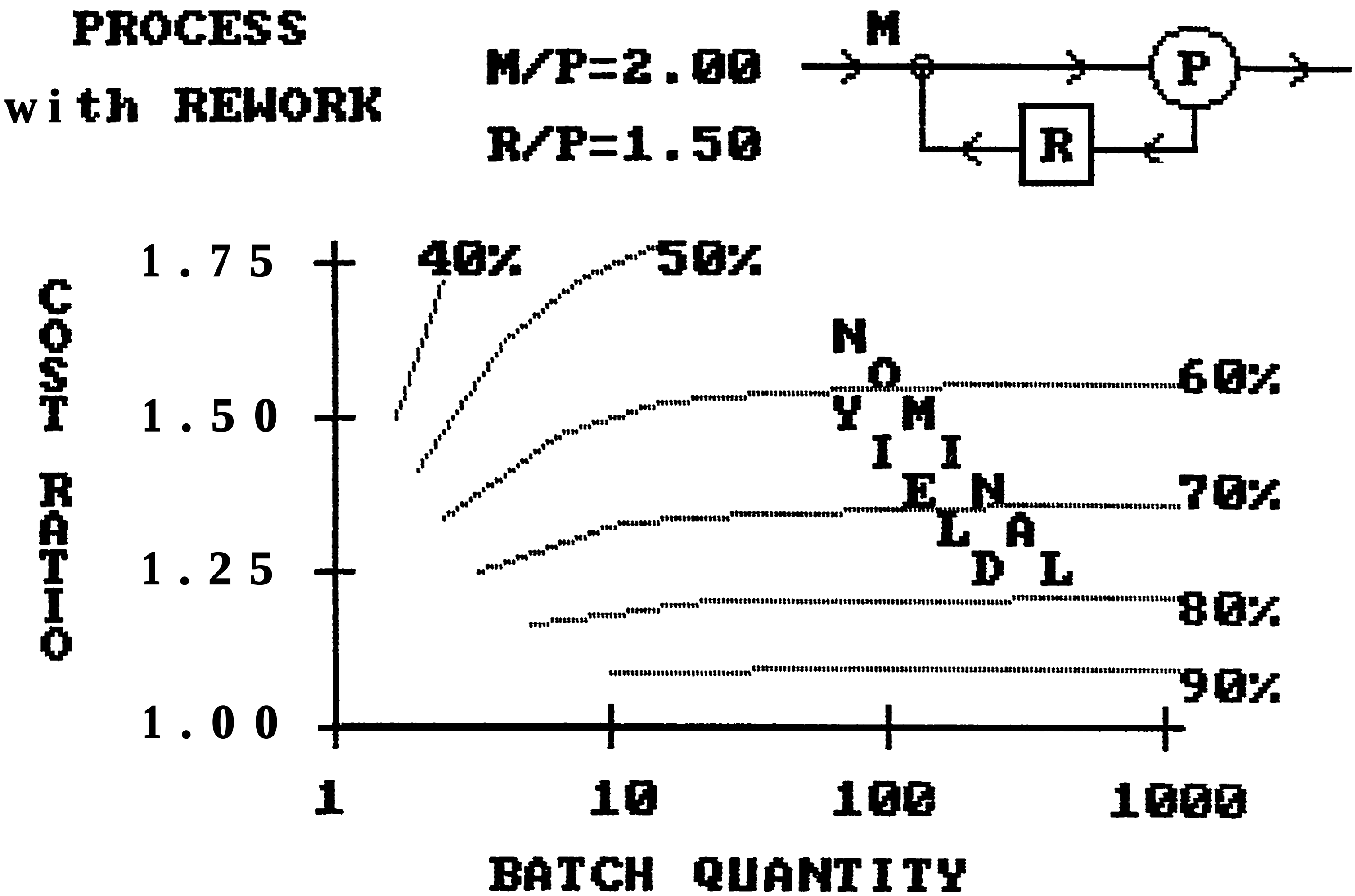

PROCESS
with REWORK
M/P=2.00
R/P=1.50
M
P
R
COST RATIO
1.75
1.50
1.25
1.00
40%
50%
60%
70%
80%
90%
NO YIELD
MINIMAL
1
10
100
1000
BATCH QUANTITY

Figure A.1

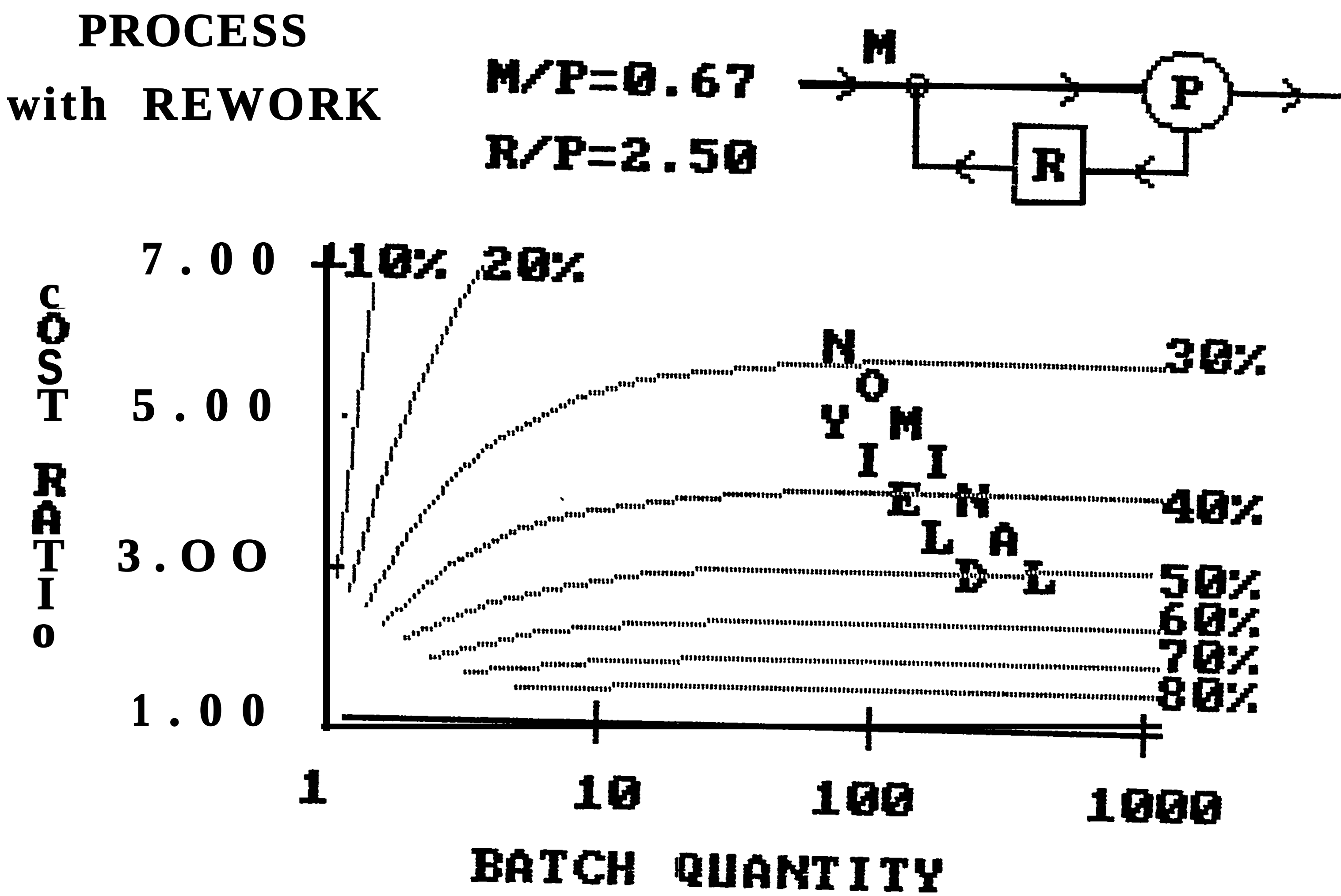

PROCESS
with REWORK
M/P=0.67
R/P=2.50
M
P
R
7.00
5.00
3.00
1.00
COST RATIO
10%
20%
30%
40%
50%
60%
70%
80%
NOMINAL YIELD
1
10
100
1000
BATCH QUANTITY

Figure A.2

when integer behavior is required (e.g. when exact physical behavior must be established), y must be equal to [1 - 1/n q] only. Then (18) becomes

$$T_i = 1 + \left(\frac{1 + R_i/P_i}{1 + M_i/P_i}\right)\left(\frac{1}{\sqrt[n]{q} - 1}\right)\left(1 - \frac{1}{q}\right) \tag{19}$$

which is valid only when q has an nth root.

Since little is known quantitatively about what occurs in a shipyard, equation (18) was used as the basis for cost comparisons in this report.

<u>Shipyard Application</u> (Three Single-Level Processes)

Each of the three outfitting levels in a shipyard can be cost analyzed using equation (18) since they are independent of each other. There is some (generally qualitative) data concerning the ratio of actual cost for the three levels

Level 1 (On Unit) 1
Level 2 (On Blocks) 3
Level 3 (On Board) 10

Actual values can be easily manipulated in program SHIPYRDY to establish sensitivity.

Let's do some cost comparisons so that the nominal yield can be established. First, rewrite (18) as

$$\frac{(T_k - 1)}{\left(1 - \frac{1}{q}\right)} \quad \left(\frac{1 + M_k/P_k}{1 + R_k/P_k}\right) = \left(\frac{1}{y_k} - 1\right) \tag{20}$$

or

$$\boxed{y_k = \frac{1}{\left(\dfrac{T_k - 1}{1 - \dfrac{1}{q}}\right)\left(\dfrac{1 + M_k/P_k}{1 + R_k/P_k}\right) + 1}} \tag{21}$$

Equation (21) will establish nominal yield if we know the absolute cost ratio. At this point, only relative information has been provided. Therefore, it is necessary to use equation (18) in the following way

$$\frac{T_k}{T_i} = \frac{1 + \left(\dfrac{1 + R_k/P_k}{1 + M_k/P_k}\right)\left(\dfrac{1}{y_k} - 1\right)\left(1 - \dfrac{1}{q}\right)}{1 + \left(\dfrac{1 + R_i/P_i}{1 + M_i/P_i}\right)\left(\dfrac{1}{y_i} - 1\right)\left(1 - \dfrac{1}{q}\right)} \tag{22}$$

Let's use i=l and k=3, then

$$\frac{T_3}{T_1} = \frac{1 + \left(\dfrac{1 + R_3/P_3}{1 + M_3/P_3}\right)\left(\dfrac{1}{y_3} - 1\right)\left(1 - \dfrac{1}{q}\right)}{1 + \left(\dfrac{1 + R_1\ \ P_1}{1 + M_1\ \ P_1}\right)\left(\dfrac{1}{y_1} - 1\right)\left(1 - \dfrac{1}{q}\right)} \tag{23}$$

To simplify (assume that Y1 is specified), let

$$F_1 = \left(\frac{T_3}{T_1}\right)\left|\ 1 + \left(\frac{1 + R_1/P_1}{1 + M_1/P_1}\right)\left(\frac{1}{y_1} - 1\right)\left(1 - \frac{1}{q}\right)\right| \tag{24}$$

Substitution of (24) into (23) and rearranging leads to

$$Y_3 = \frac{1}{1 + \left(\dfrac{F_1 - 1}{1 - \frac{1}{q}}\right)\left(\dfrac{1 + M_3/P_3}{1 + R_3/P_3}\right)} \tag{25}$$

What if we change all the M_i/P_i, R_i/P_i and T_i and to more optimistic values? The following general conditions apply (assume constant material cost)

1. Reduction in process cost

$$P_{i_{NEW}} = \left[\frac{\left(M_i/P_i\right)_{OLD}}{\left(M_i/P_i\right)_{NEW}}\right] P_{i_{OLD}}$$

or:

$$\left(\frac{M_i}{P_i}\right)_{NEW} = \left(\frac{P_{i\ OLD}}{P_{i\ NEW}}\right)\left(\frac{M_i}{P_i}\right)_{OLD}$$

2. Reduction in rework cost

$$R_{i_{NEW}} = \left[\frac{\left(R_i/P_i\right)_{NEW}}{\left(R_i/P_i\right)_{OLD}}\right]\left(\frac{P_{i\ NEW}}{P_{i\ OLD}}\right) R_{i\ OLD}$$

or:

$$\left(\frac{R_i}{P_i}\right)_{NEW} = \left(\frac{R_{i_{NEW}}}{R_{i_{OLD}}}\right)\left(\frac{P_{i_{OLD}}}{P_{i_{NEW}}}\right)\left(\frac{R_i}{P_i}\right)_{OLD} \tag{27}$$

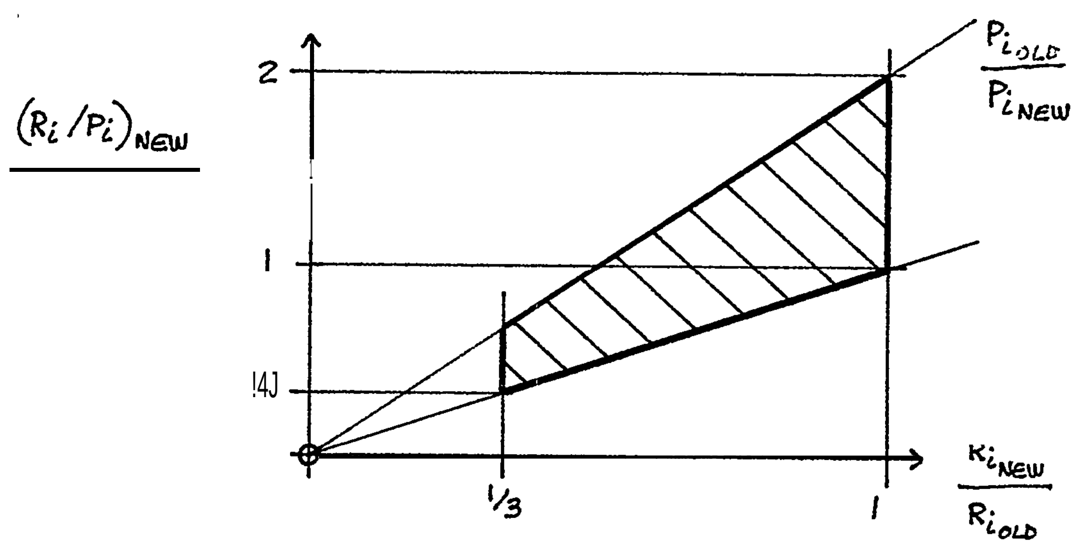
We should be realistic and state that

$$1 \leq \left(\frac{P_{i_{OLD}}}{P_{i_{NEW}}}\right) \leq 2 \,, \qquad \frac{1}{3} \leq \left(\frac{R_{i_{NEW}}}{R_{i_{OLD}}}\right) \leq 1$$

Then, equation (26) can be rewritten

$$(M_i/P_i)_{OLD} \leq (M_i/P_i)_{NEW} \leq 2(M_i/P_i)_{OLD}$$

Equation (27) can not be rewritten (using these limits) so easily. First we need to graph the behavior



Overall, we can write

$$(1/3)(R_i/P_i)_{OLD} \le (R_i/P_i)_{NEW} \le 2(R_i/P_i)_{OLD}$$

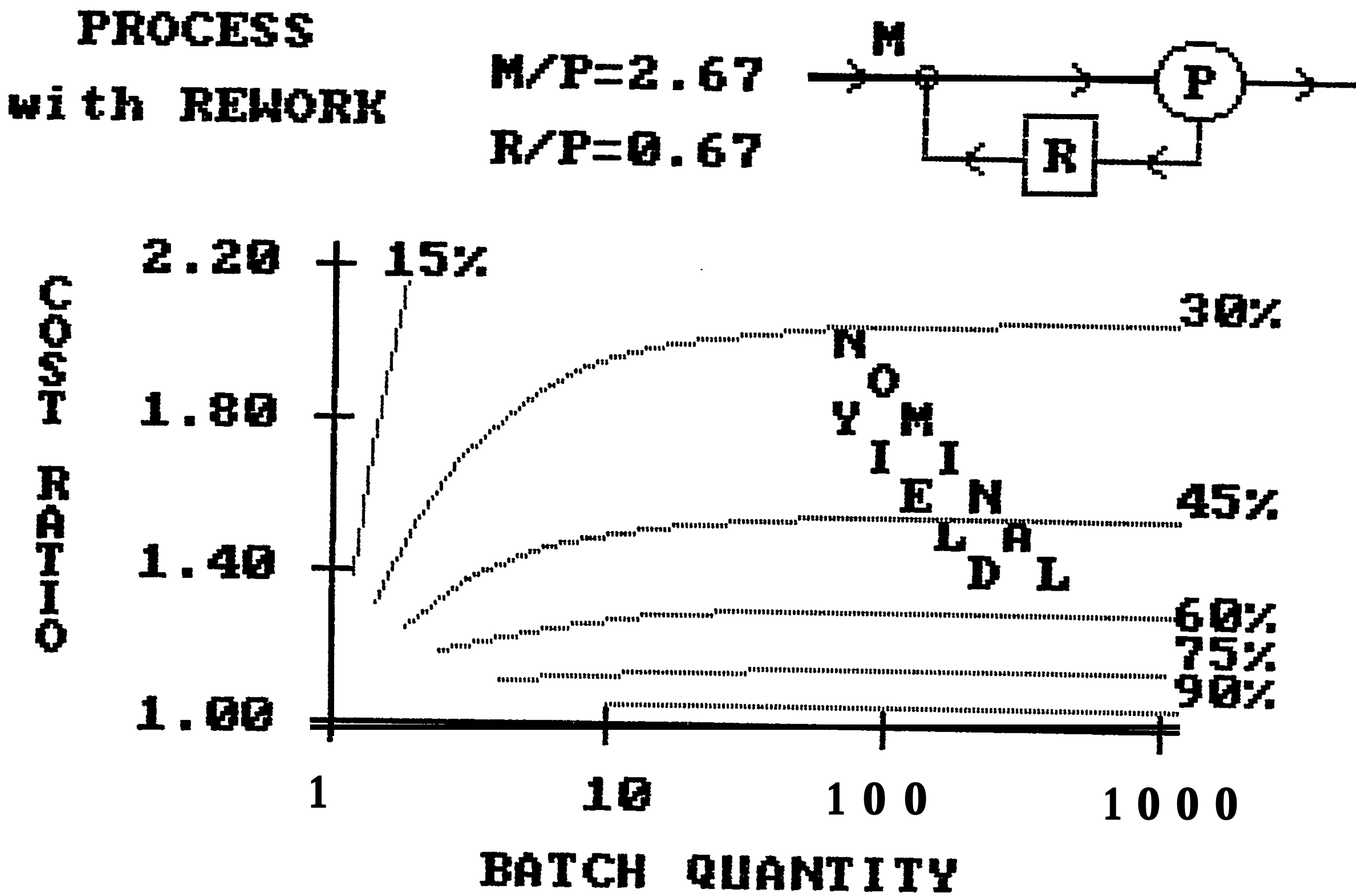
subject to the limitations seen in the graph. We can ***then*** establish revised values for R_i/P_i and M_i/P_i.

	OLD	NEW
R_2/P_2	2.00	0.67 → 4.00
M_2/P_2	1.33	1.33 → 2.67
R_3/P_3	2.50	0.83 → 5.00
M_3/P_3	0.67	0.67 → 1.33

Review of equation (18) shows that cost is least when R_i/p_i is least, M_i/P_i is largest and y is largest. Figure 3 displays level 2 (ON BLOCKS) best case data while figure 4 displays level 3 (ON BOARD) best case data. The relationship of cost ratio (Ti) to nominal yield rate is readily apparent.

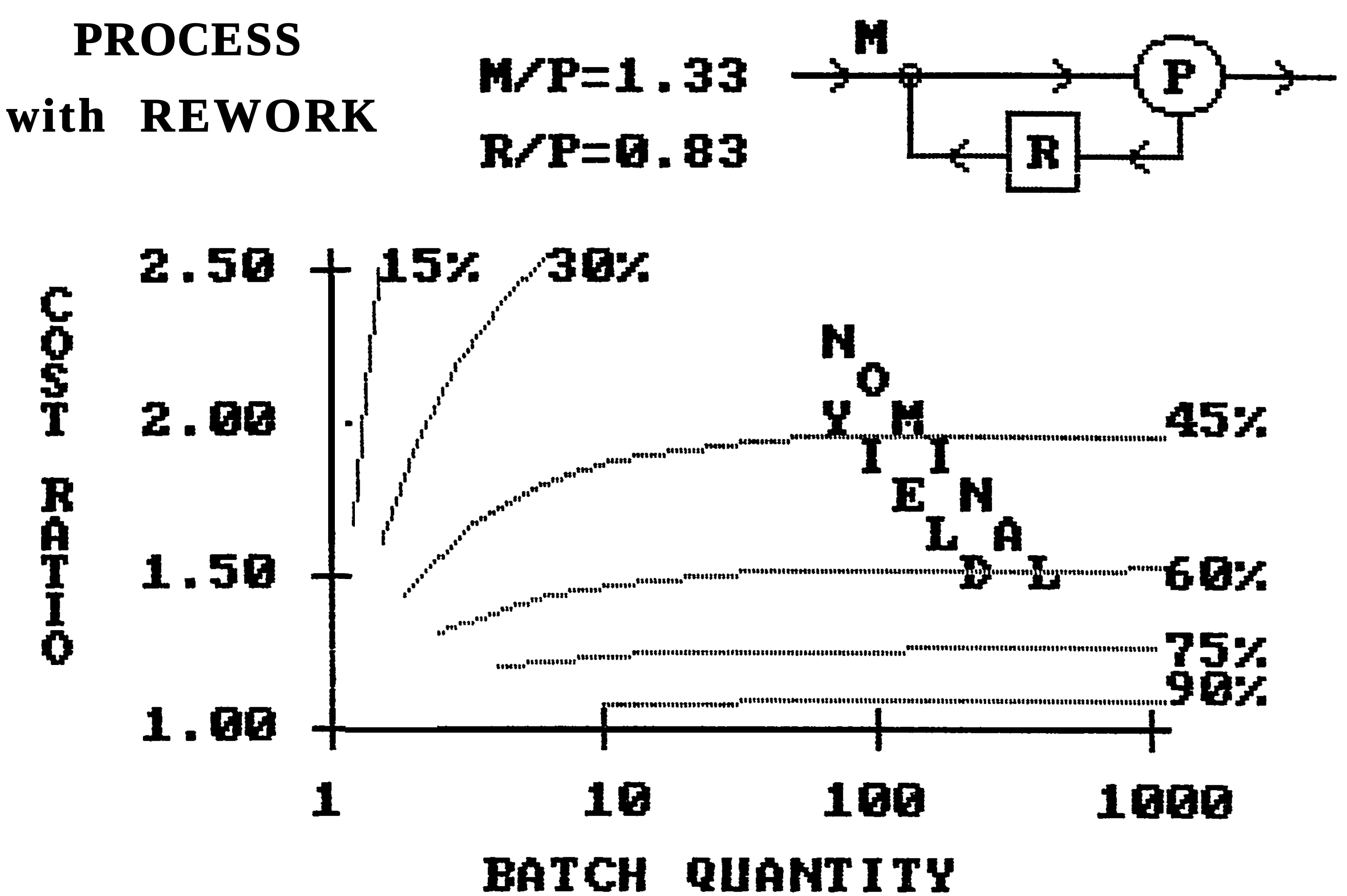
Again let q=6 items and choose $T_2/T_1 = 1.25$ and $T_3/T_1 = 1.50$. we assume that ultimate process yield cannot be perfect. Figure 5 exhibits the new yield data when level 1 yield is 90%. Surprisingly, the nominal yield at levels 2 and 3 is almost constant.

For contrast, choose the opposite conditions (Ri/Pi maximum, M_i/P_i minimum). Figure 6 shows that the nominal yield at levels 1 and 2 is again practically constant but significantly increased. This should not be particularly surprising since we required a very low relative cost ratio with high cost of rework; that can only occur if yield is high.



PROCESS
with REWORK
M/P=2.67
R/P=0.67
M
P
R
COST RATIO
2.20
1.80
1.40
1.00
15%
30%
45%
60%
75%
90%
NOMINAL
YIELD
1
10
100
1000
BATCH QUANTITY

Figure A.3

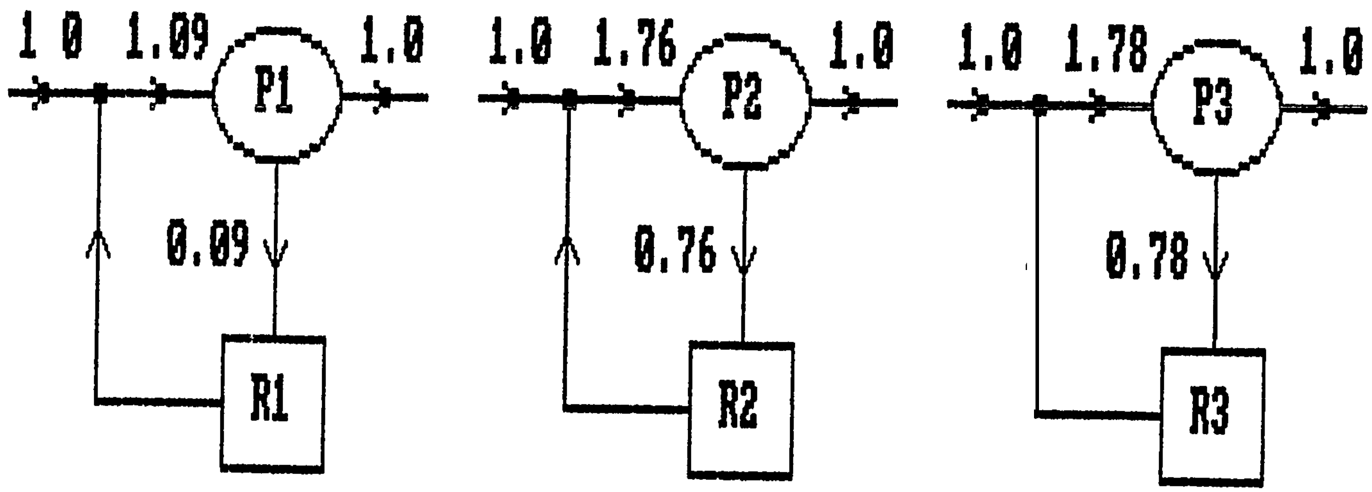


PROCESS
with REWORK
M/P=1.33
R/P=0.83
M
P
R
COST RATIO
2.50
2.00
1.50
1.00
15%
30%
45%
60%
75%
90%
NO YIELD
MAXIMAL
1
10
100
1000
BATCH QUANTITY

Figure A.4

SHIPYARD RELATIVE COST ANALYSIS 6 ITEMS

	ON UNIT	ON BLOCKS	ON BOARD
REL COST:	1.00	1.25	1.50
REW/PRC:	1.50	0.67	0.83
MTL/PRC:	2.00	2.67	1 33

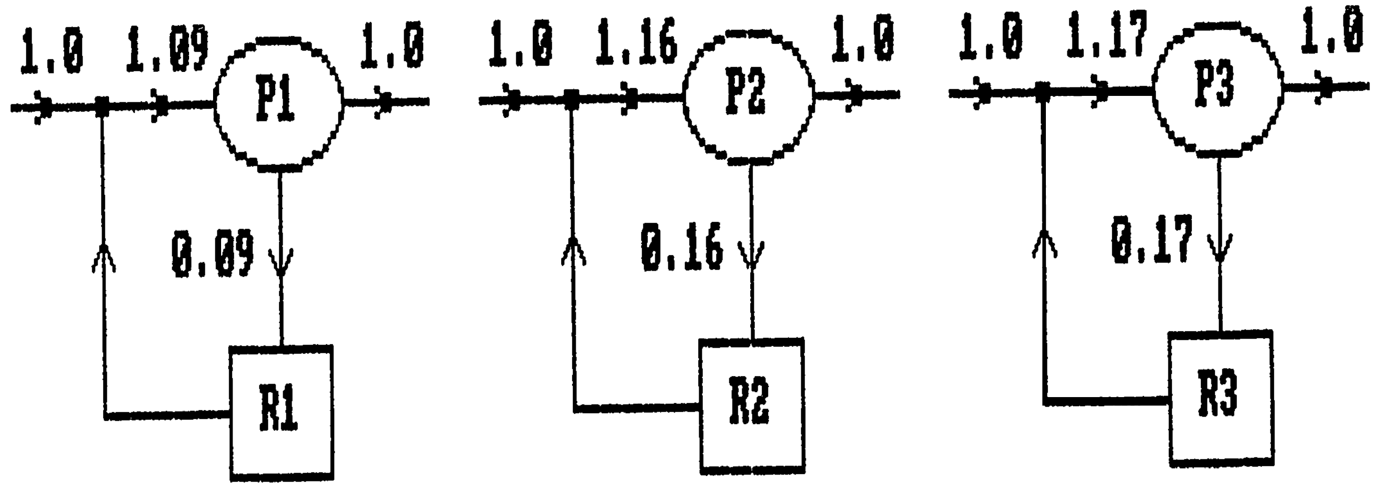


YIELD:	0.9000	0.5223	0 5154

Figure A.5

SHIPYARD RELATIVE COST ANALYSIS 6 ITEMS

	ON UNIT	ON BLOCKS	ON BOARD
REL COST:	1.00	1.25	1.50
REW/PRC:	1.50	4.00	5.00
MTL/PRC:	2.00	1.33	0.67



YIELD:	0.9000	0.8375	0.8297

Figure A.6

APPENDIX B

MANIFACTURER'S INFORMATION ABOUT SPIRAL DUCT FORMING MACHINES

This appendix contains samples of manufacturer’s information from two builders of spiral duct and pipe forming machines. A typical machine for making duct in the 6" to 18" diameter range costs between $70,000 and $125,000 depending on options ordered. Some necessary options are forming rolls for different metal gages and rolling heads for determining the duct’s diameter. Other options include heads for welding the seam instead of lock-forming it. Tubes can be formed with corrugations or thin ribs, both of which add strength and allow thin walls to be used.

One width of metal strip can be used for a wide range of tube diameters, and tubes of arbitrary length can be made, subject to space limitations in the shop. This means that inventory and ordering problems are reduced, and tubes can be made as needed. Change over times are quoted at 5 minutes.

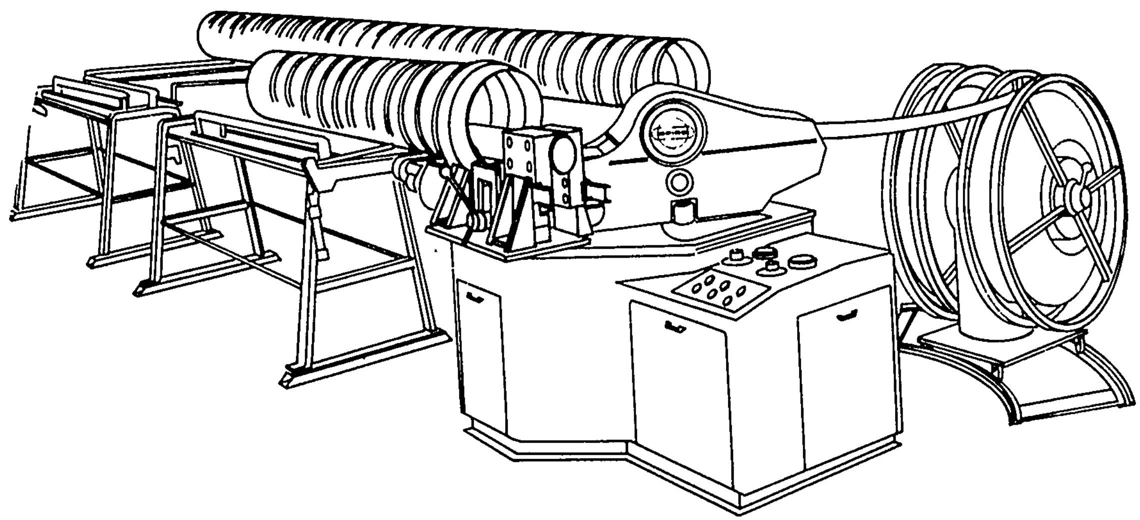


Figure B.1: Spiral Duct Forming Machine

SHIP PRODUCT

FACILITIES I

OUTFITTING AND

INDUSTRIAL ENGINEER

SHIPBUILDING STAN

DESIGN / PRODUCTION IN

HUMAN RESOURCE IN

SURFACE PREPARATION

FLEXIBLE A

TECHNOLOG

WE

EDUC